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Pressurizer Nozzle Dissimilar Metal Weld Advanced Finite Element Analyses

NRC Public Meeting
August 9, 2007

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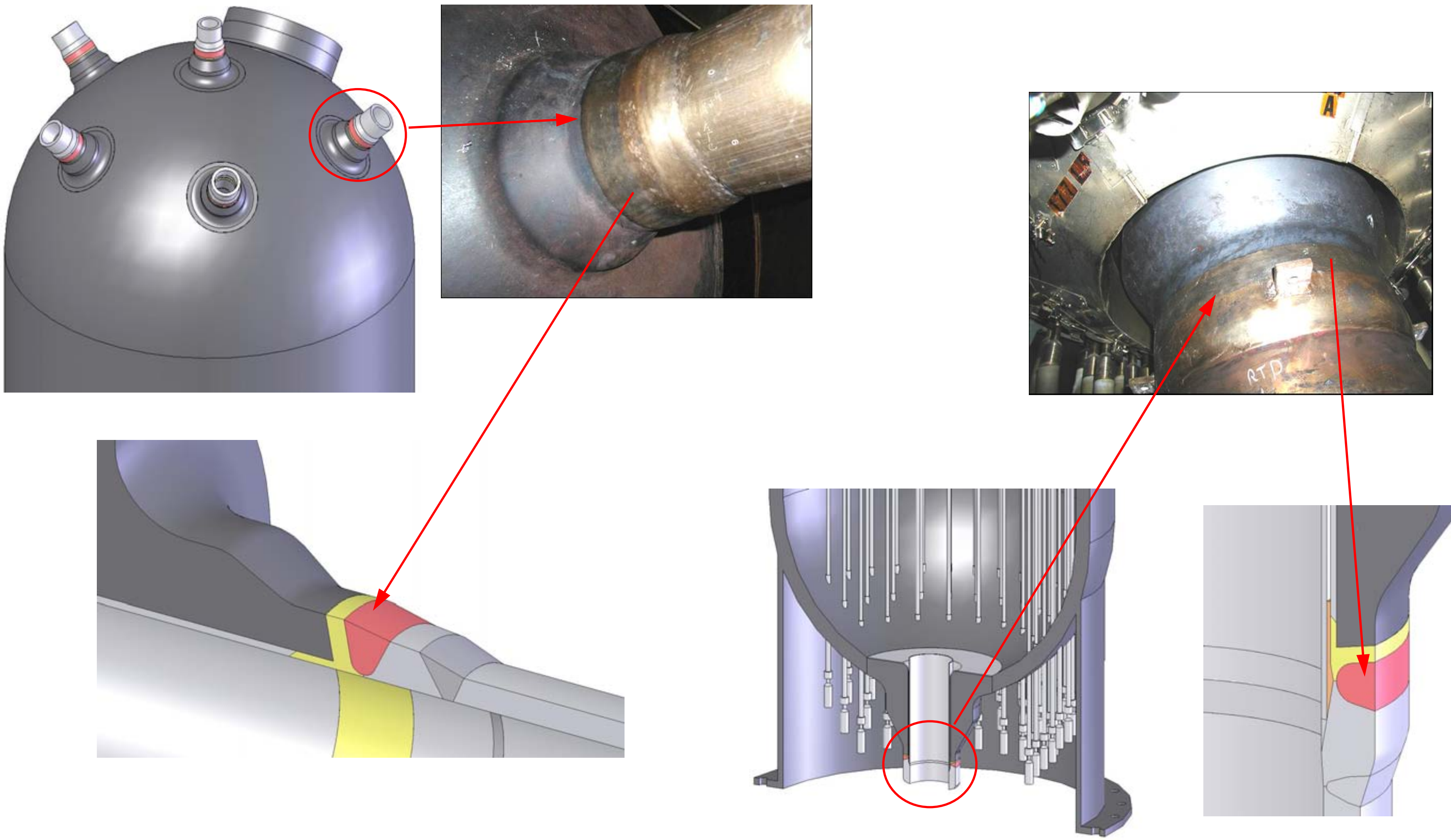
Dominion Engineering, Inc.

Topics
(EPRI 1015383 (MRP-216) Final Report Outline)

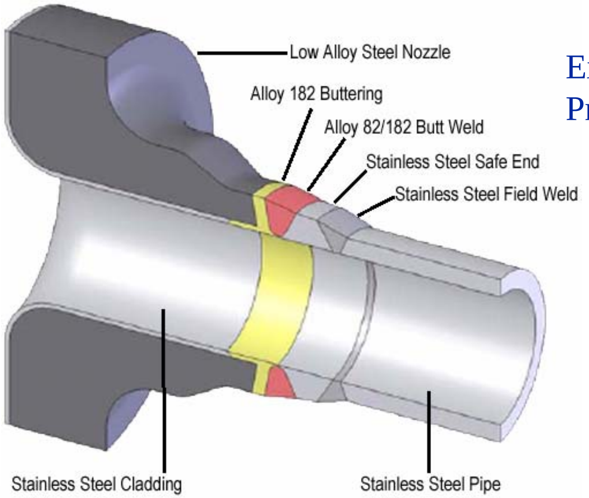
1. Introduction (Background, Objective, and Approach)
2. Plant Inputs (Geometry, Fabrication, and Loads)
   - Appendix A: Fabrication Details
3. Welding Residual Stress
4. Crack Growth Modeling
5. Critical Crack Size Calculations
   - Appendix B: Effects of Secondary Stresses on Surge Line Crack Stability
   - Appendix C: Pipe Bending with a Through-Thickness Crack
6. Leak Rate Modeling
   - Appendix D: Scatter in Leak Rate Predictions
7. Sensitivity Case Matrix
8. Summary and Conclusions
   - Appendix E: Probabilistic Evaluation

Background

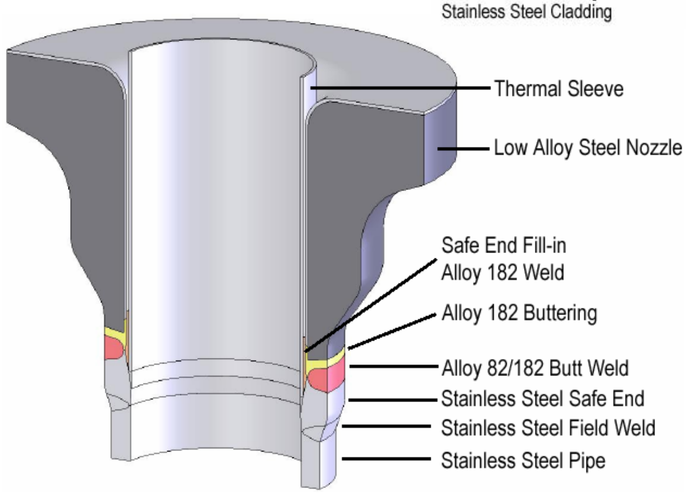
Pressurizer Top & Bottom Head Nozzles



Background
Pressurizer Top & Bottom Head Nozzles (cont'd)

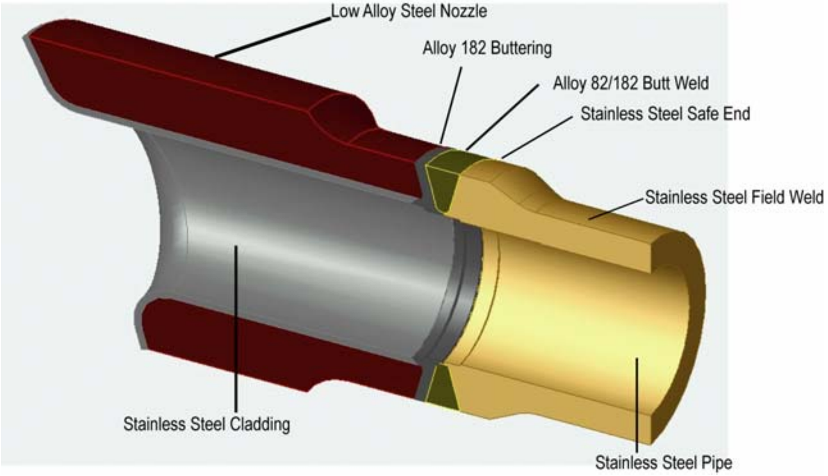


Example Westinghouse Pressurizer Safety/Relief Nozzle



Example Westinghouse Pressurizer Surge Nozzle

Example CE Pressurizer Safety/Relief Nozzle



WC Inspection Results and Evaluation

Indication Characterization – October 2006

					2006 Indications				
Nozzle	Circumference (in)	Outside Diameter (in)	Thickness (in)	Inside Diameter (in)	OD Lemgth (inches)	Arc Length (2) (deg)	Maximum Depth (1) (%)	Depth (in)	Aspect Ratio (3)
Safety C	25.0	7.96	1.32	5.32	3.75	54	23	0.30	8
Relief	25.0	7.96	1.32	5.32	11.50	166	26	0.34	22
Surge	47.0	14.96	1.45	12.06	1.00	8	<10 (4)	---	---
	47.0	14.96	1.45	12.06	2.75	21	25	0.36	6
	47.0	14.96	1.45	12.06	5.00	38	31	0.45	9
				Surge Nozzle Totals =>	8.75	67			

Highlighted data represents values reported to the NRC by Wolf Creek. Other values are calculated by geometry.

(1) Average depth from 45 and 60 degree angle UT probes at maximum depth location.

(2) Calculated from OD length and circumference.

(3) Calculated from ID arc length and depth.

(4) Indication found but no measurable depth could be determined.

Project Objective

- To evaluate the viability of detection of leakage from a through wall flaw to preclude the potential for rupture of pressurizer nozzle DM welds, given the potential concern about growing circumferential stress corrosion cracks.
- This study is specific to the group of nine PWRs originally scheduled for performance demonstration initiative (PDI) inspection or mitigation during the spring 2008 outage season
- Commitments have been made for these nine PWRs to accelerate refueling outages or take mid-cycle outages. Should this study demonstrate flaw stability via sufficient time from initial detectable leakage until pipe rupture, as demonstrated to the NRC, these plants could then resume plans to perform PDI inspection or mitigation during the spring 2008 outage season.

Project Oversight

- Project Team
  - Dominion Engineering (DEI)
  - Quest Reliability – (FEACrack Software Developer)
- Expert Panel
  - Established to provide review, input, and oversight of the technical issues and approaches
  - Members well known in this industry were chosen
    - Ted Anderson, Quest Reliability, LLC
    - Warren Bamford, Westinghouse
    - Doug Killian, AREVA
    - Ken Yoon, AREVA
    - Pete Riccardella, Structural Integrity Associates
    - David Harris, Structural Integrity Associates
      - included specifically for his lack of recent involvement in Alloy 600 fracture mechanics applications to bring a fresh perspective
- Interacted with NRC Counterparts in ~7 NRC public meetings

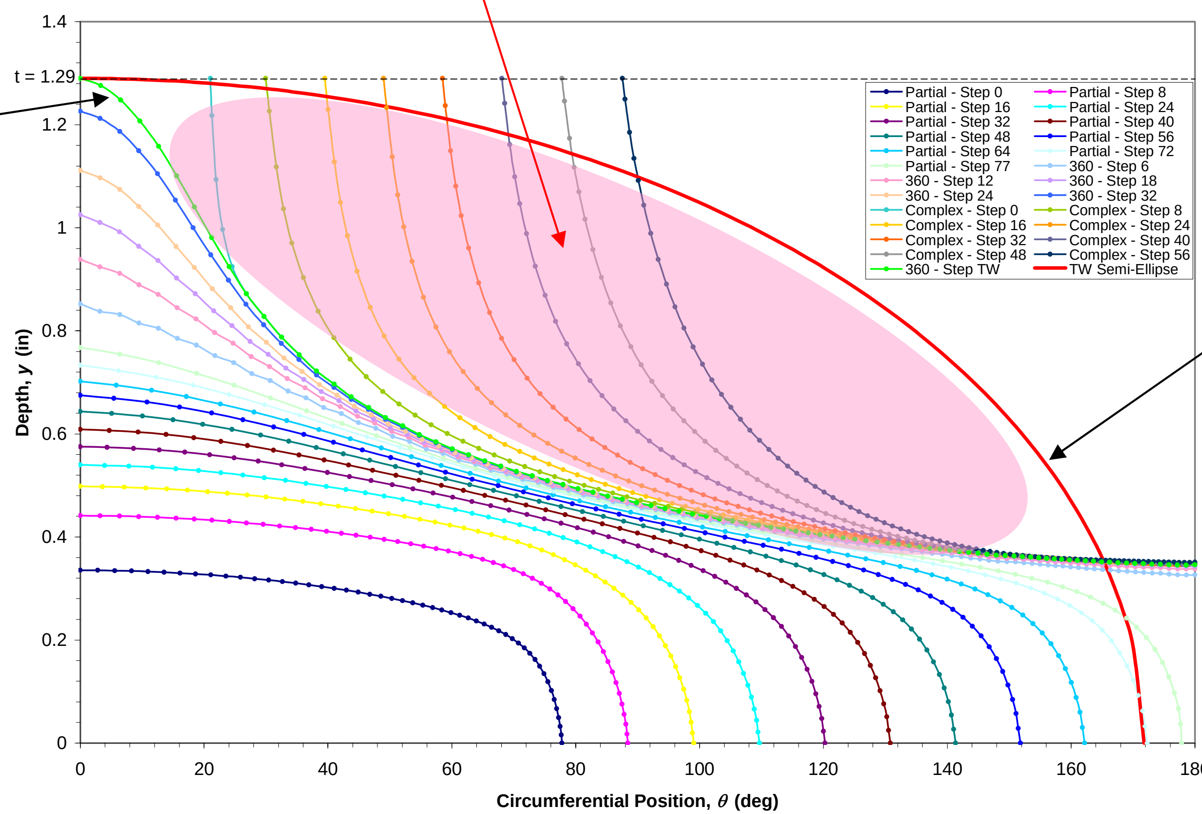
Project Approach

Artificial Conservatism of Semi-Elliptical Crack Assumption

Semi-ellipse assumption over predicted extent of cracked material in this zone vs. the arbitrary shape methodology for the Wolf Creek nozzle benchmark run

Arbitrary Crack Shape at Initial Through Wall

Growth at each point on the crack front as a function of the stress intensity factor calculated at that point



Semi-Ellipse Crack Shape at Initial Through Wall

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Project Approach
Key Project Activities

- Software capability development within FEACrack
- Develop and execute an analysis parametric sensitivity case matrix
  - Develop and apply a sensitivity matrix of welding residual stress (WRS) profiles, including weld repairs
  - Crack growth calculations for custom crack shape
- Critical crack size calculations to define the end point for the crack growth calculation
- Leak rate calculations - PICEP and SQUIRT models
- Software verification and benchmarking
- Validation
- Expert panel input and review throughout the project

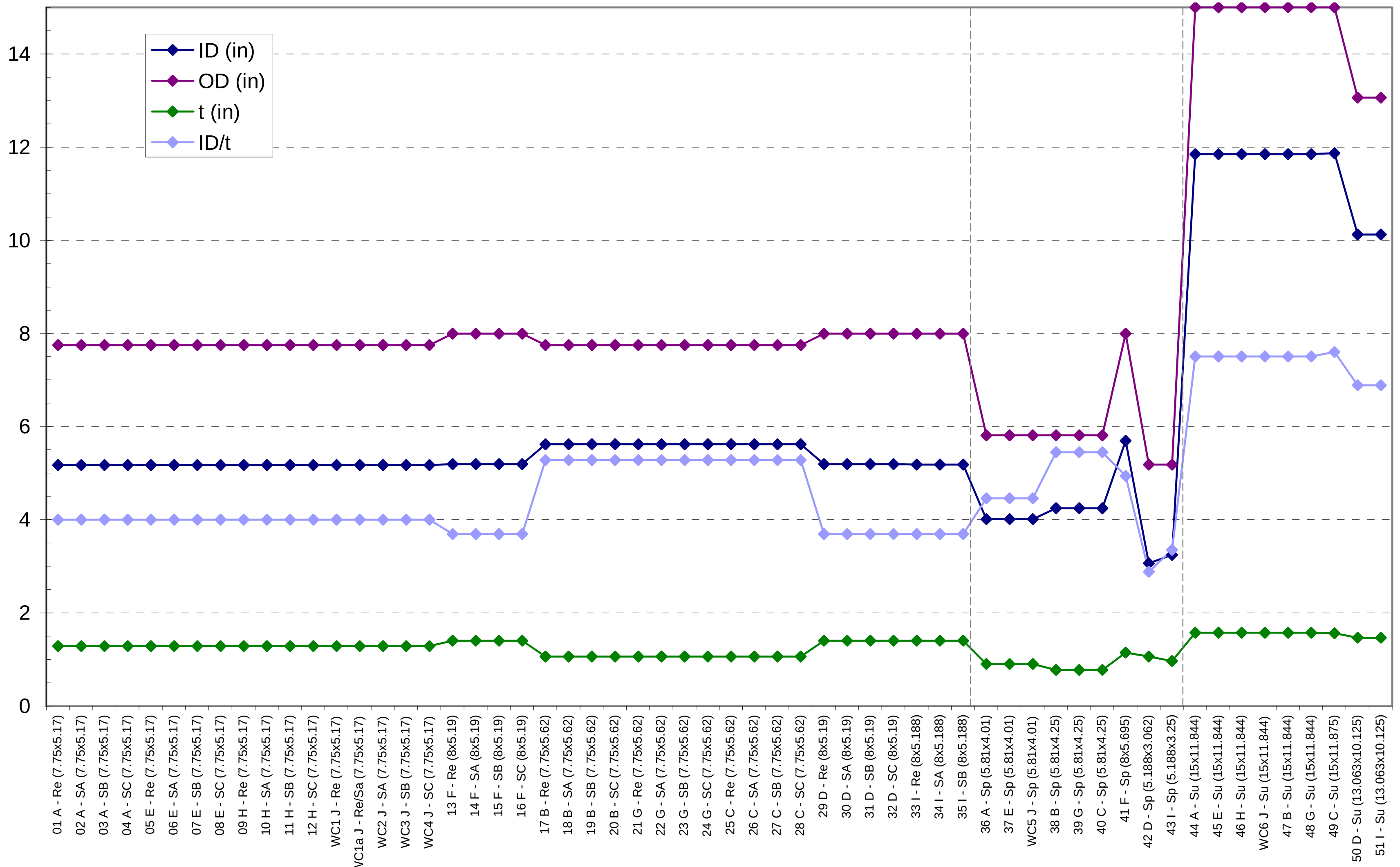
Plant Inputs
Plant Specific Geometries

– **Safety and Relief nozzles**
  - 35 safety and relief (S&R) nozzles (1 plant has only three S&R nozzles)
    – Represented by 5 geometric configurations

– **Spray nozzles**
  - 8 spray nozzles (1 examined by PDI process in 2005)
    – Represented by 4 geometric configurations

– **Surge nozzles**
  - 8 surge nozzles (1 already overlayed)
    – Represented by 2 geometric configurations

Plant Inputs
Plant Specific Geometries



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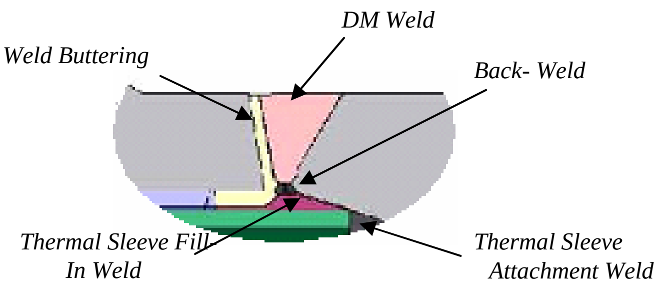
Plant Inputs
Weld Fabrication → Welding Residual Stresses

- Input obtained from design drawings & shop travelers
- Fabrication Steps affecting weld residual stress (WRS)
  - Fill-In Weld under thermal sleeve (Surge)
  - Fillet Welds (Safety/Relief)
  - Stainless steel field weld to pipe



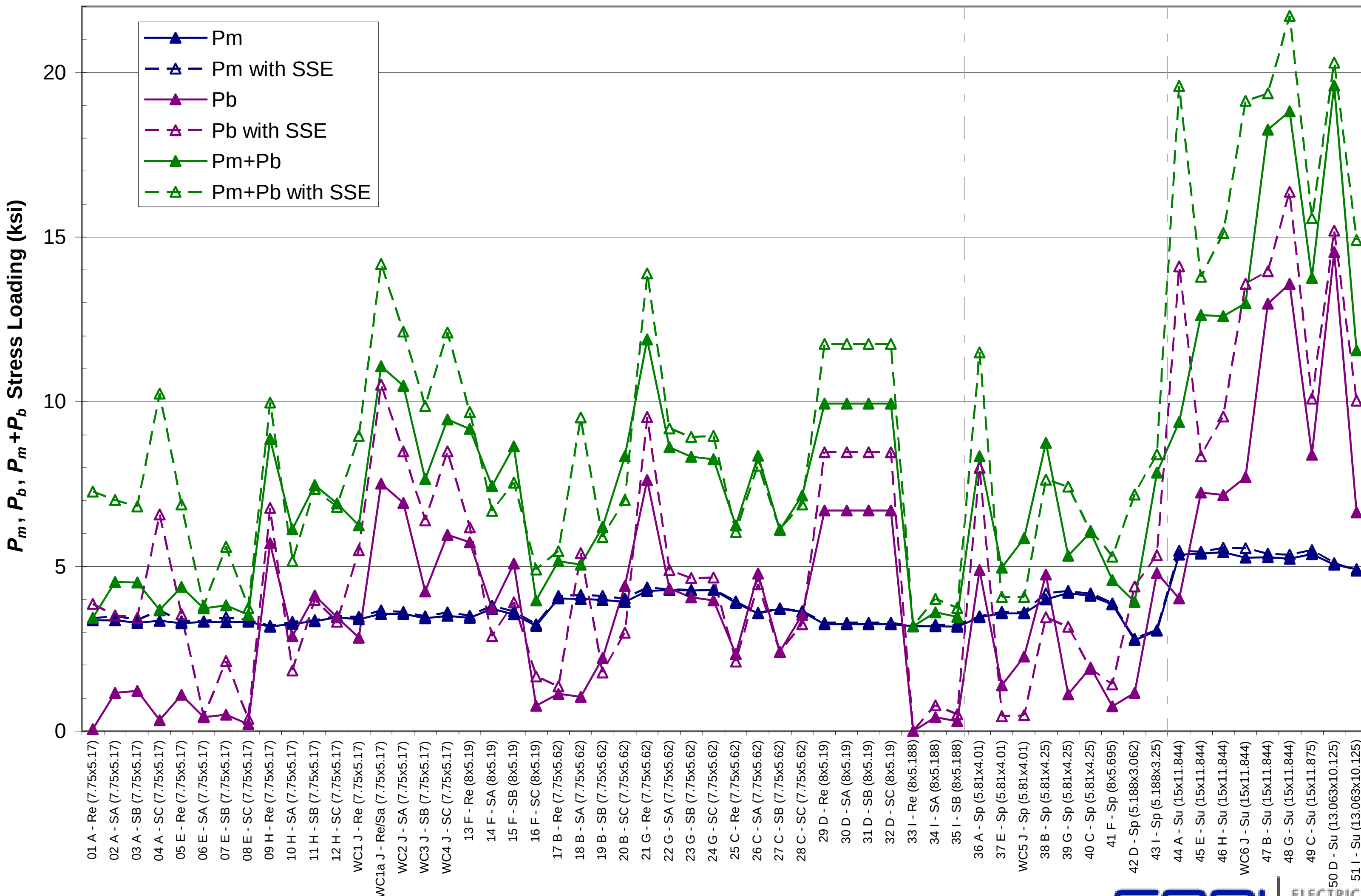
- Repairs
  - Deep ID Repairs
- Either thermal strain applied to simulate WRS profile or WRS FEA results directly input to crack growth model

Plant Inputs
Plant Specific Piping Loads

- Cover full range of piping loads for 51 subject welds:
  - All plants: 2235 psig pressure
  - Range of axial membrane stress loading, P_m
  - Range of bending stress loading, P_b
  - Crack growth loads include dead weight and normal thermal pipe expansion loads in addition to internal and crack face pressure
  - Critical crack size calculations included normal operating thermal loads in addition to internal and crack face pressure and dead weight loads

Plant Inputs
Plant Specific Piping Loads

ASME Code Nominal Stress Loading for Pressure, Dead Weight, and Normal Thermal Loading



Welding Residual Stress (WRS)
Topics

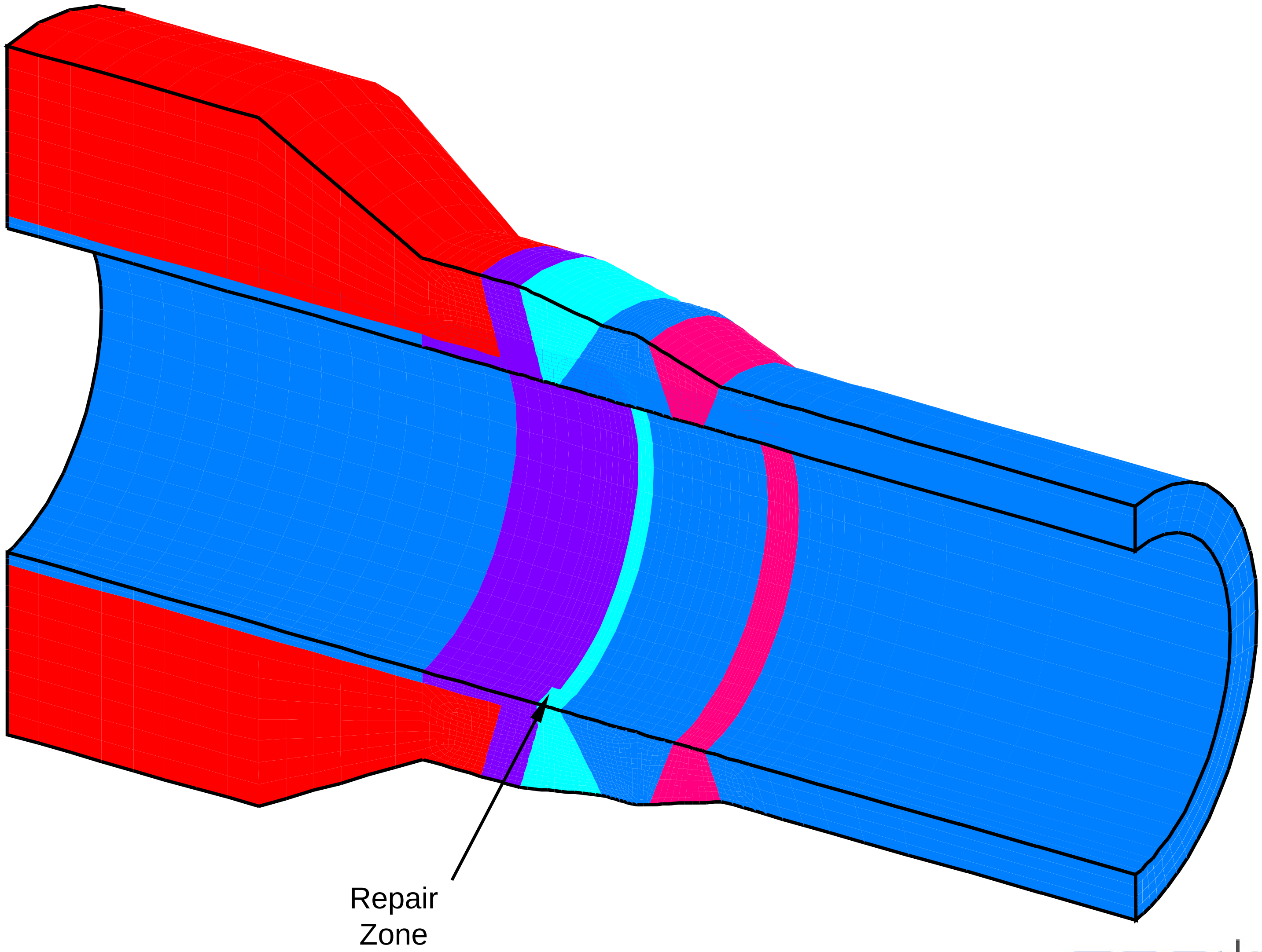
- FEA Simulations
- WRS Literature Search
- WRS Validation and Benchmarking

WRS Modeling
DEI WRS Cases

- Type 1a – Safety/Relief No Liner
  - DMW + backweld; with and without SS weld
  - DMW + backweld + safe end ID weld buildup + SS weld
  - DMW + backweld + 0.75-in deep repair, axisymmetric and 0.9-in on ID (3D)
- Type 2b – Safety/Relief w/ Liner
  - DMW + backweld + fillet weld + SS weld
- Type 8 – Surge (W)
  - DMW + backweld + Fill-In; with and without SS weld
  - DMW + repair + Fill-In + SS weld
  - DMW + backweld + 0.6" thick Fill-In
- Type 9 – Surge (CE)
  - DMW + final machining (no SS weld)

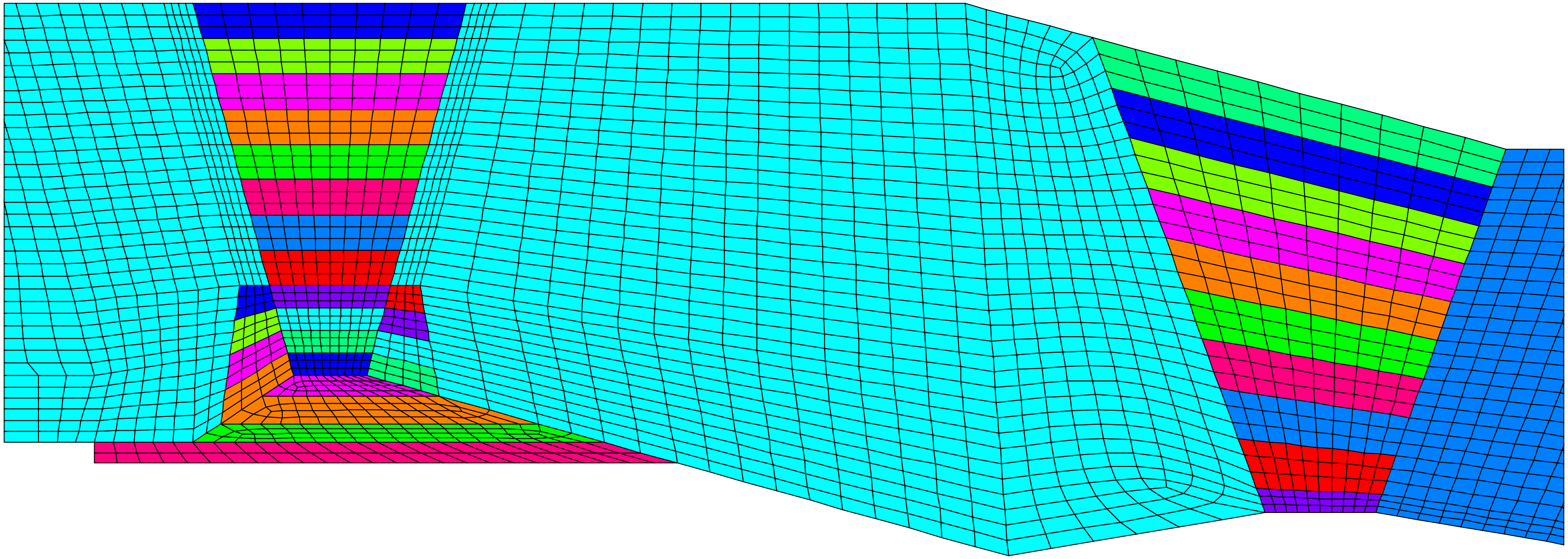
WRS Modeling

Safety/Relief Nozzle 3D Repair Model Geometry

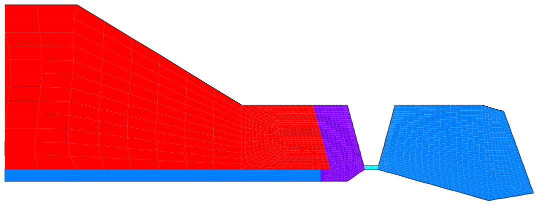


WRS Modeling

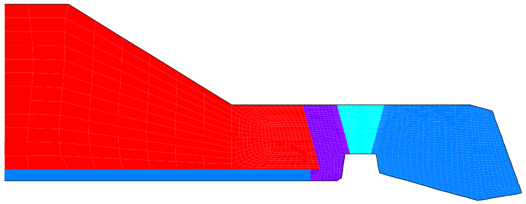
Type 8 Surge Nozzle Model – Element Mesh and Weld Layers



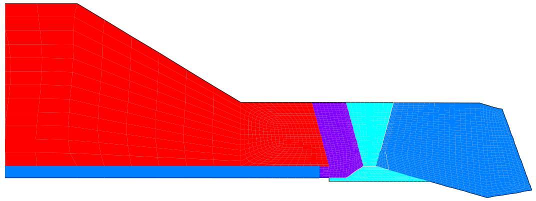
WRS Modeling
Type 8 Surge Nozzle Analysis Progression



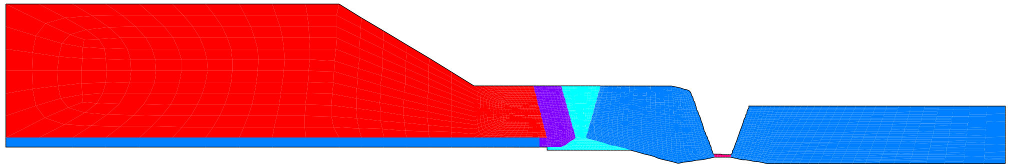
Starting Model



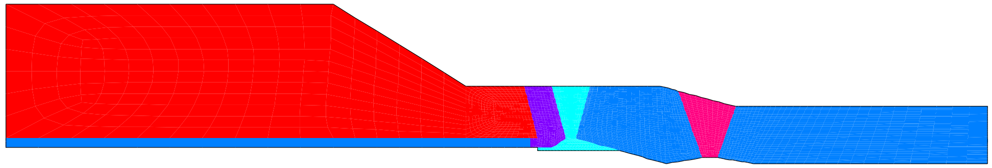
Repair Model



DMW (11 +1 layers) Followed by
Fill-in Weld (4 layers)



Begin SS Weld (8 layers)



Model Complete

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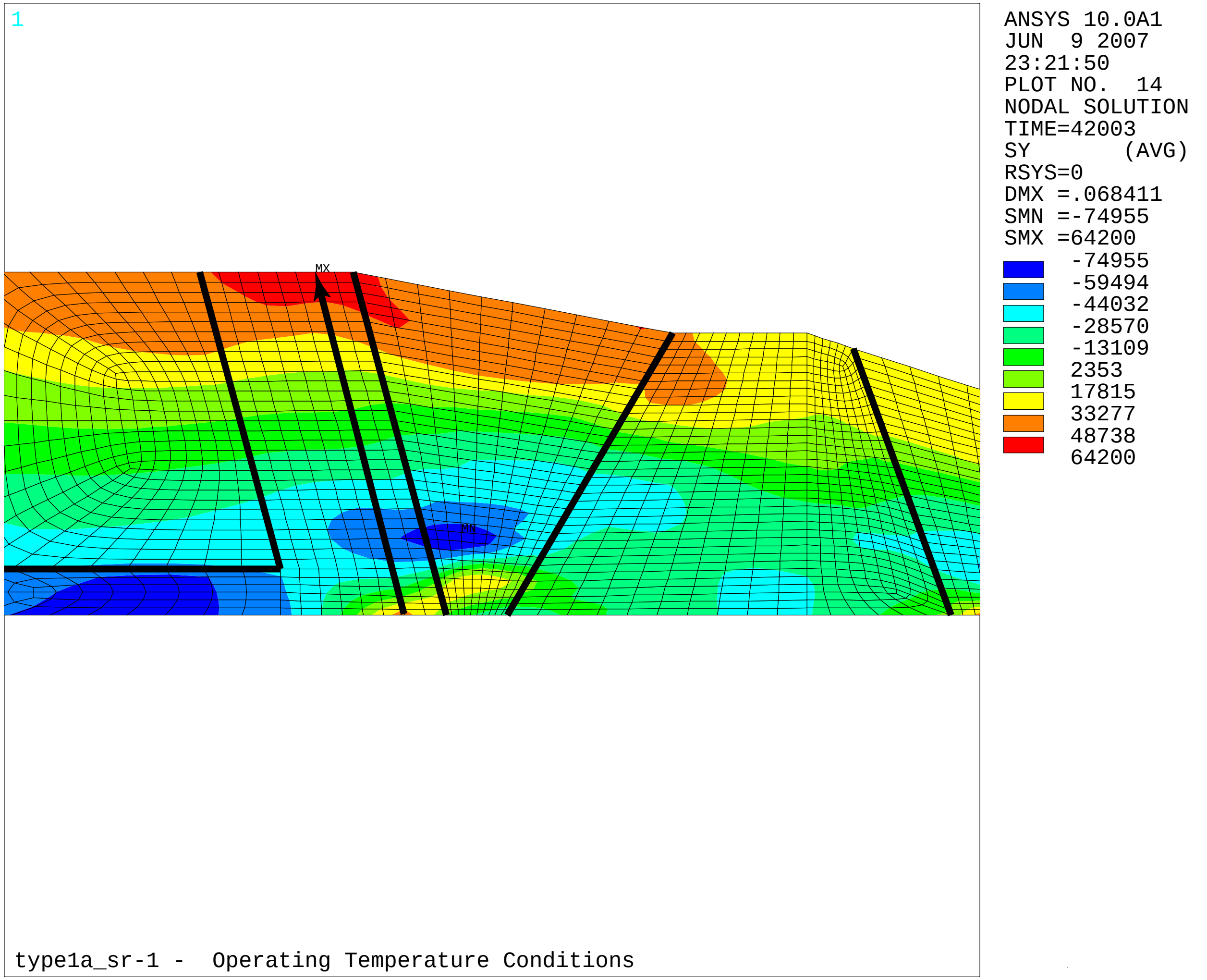
WRS Modeling

Example Stress Contour Result: Axial Stress at Normal Operating Temperature for Safety/Relief Nozzle (DMW + back-weld + SS weld)



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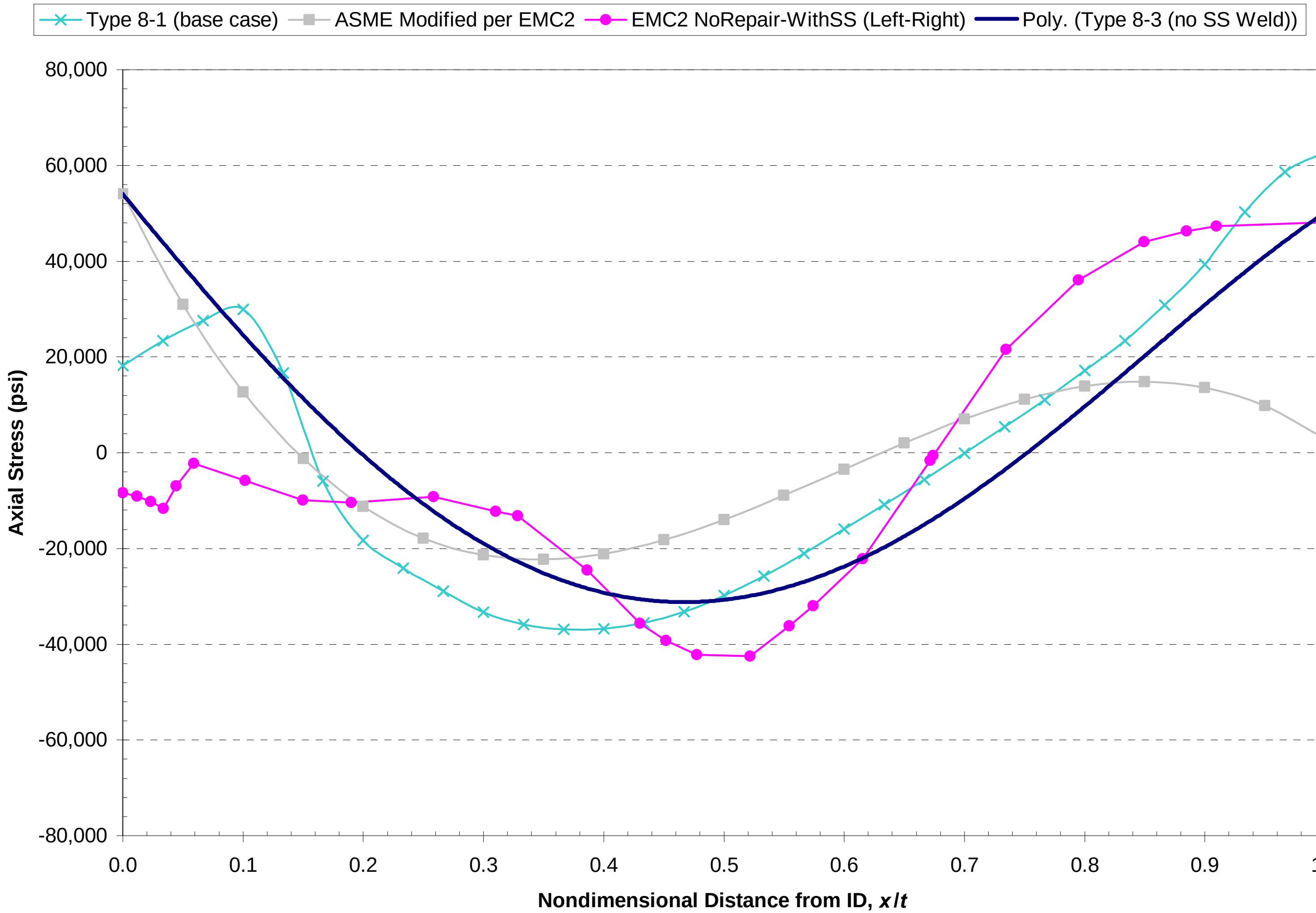
WRS Modeling

WRS Fit for Type 8 Surge Nozzle Excluding Effect of Stainless Steel Weld (Applied in Case 17b) Compared to DEI and EMC2 WRS FEA Results Including Effect of Stainless Steel Weld



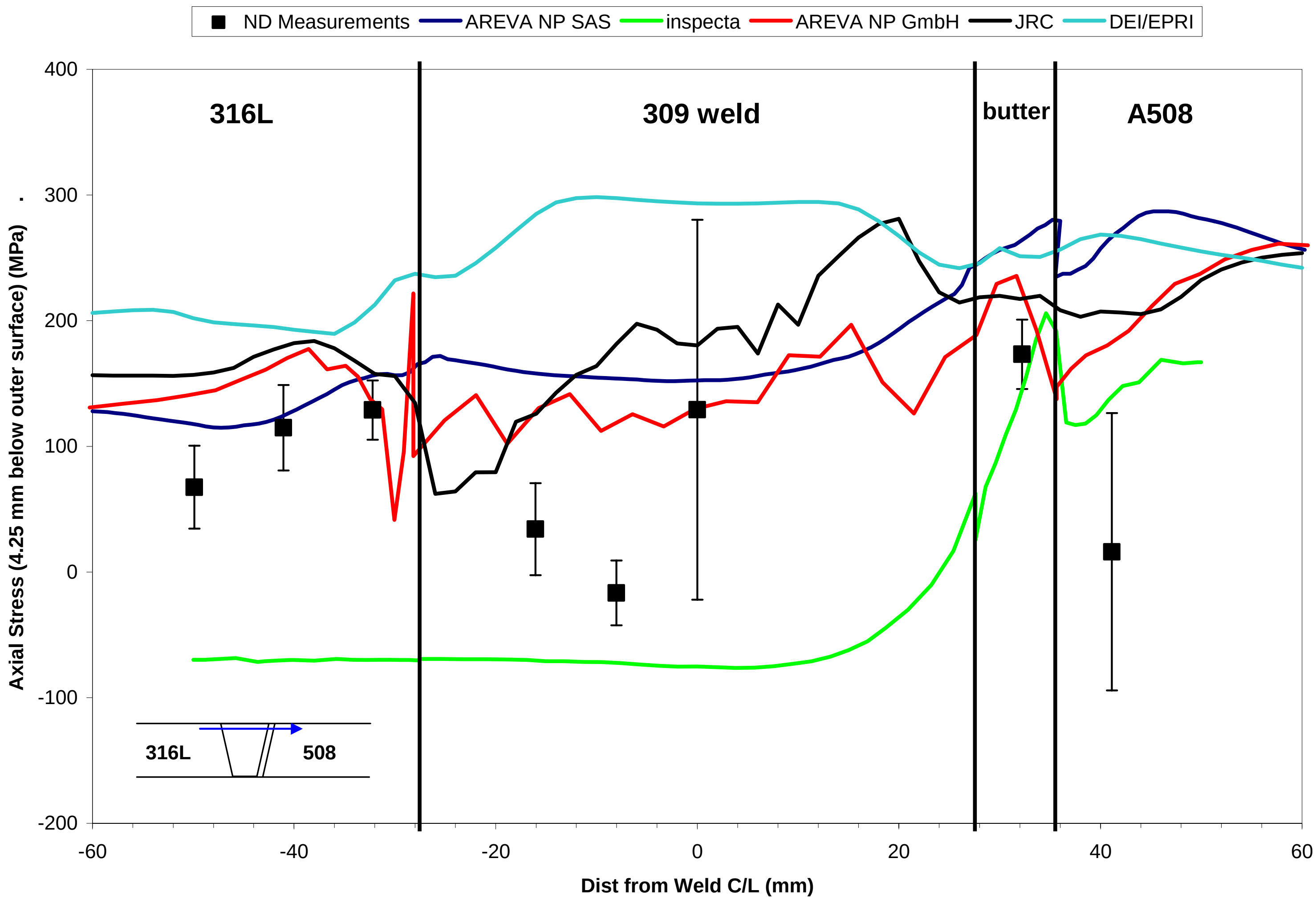
WRS Literature Search

Conclusions

- Piping Butt Welds without Repairs:
  - Stress measurements show that welding start/stops can produce variations in axial and hoop stress on the order of or greater than the material yield strength over circumferential arc lengths of 15° to 20°
- Piping Butt Welds with Repairs:
  - Weld repairs generally increase the magnitude of maximum tensile axial residual stress
  - Location of maximum axial tensile stresses can be in the repair zone or possibly opposite the repair zone depending on the location of the repair relative to the original weld start/stop location
  - Weld cap removal provides little benefit in reducing welding residual stresses, particularly on the weld ID
  - Short, deep repairs generally result in greater increases in axial tensile residual stresses

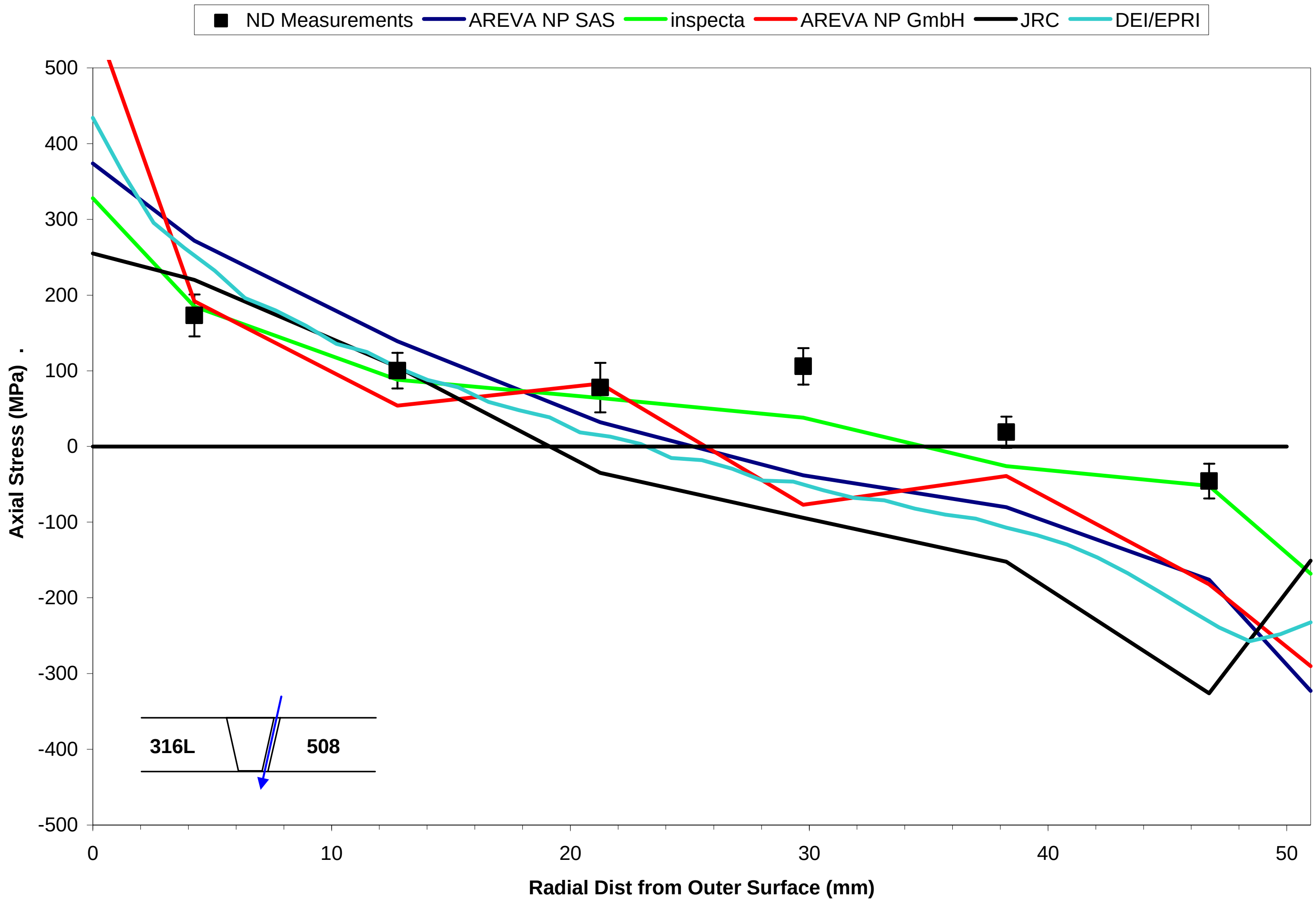
WRS Validation and Benchmarking

EU Mockup—DEI Axial Stress (4.25 mm Below the Outer Surface)



WRS Validation and Benchmarking

EU Mockup—DEI Butter Axial Stress (Through-Wall Section at Butter Layer Center)



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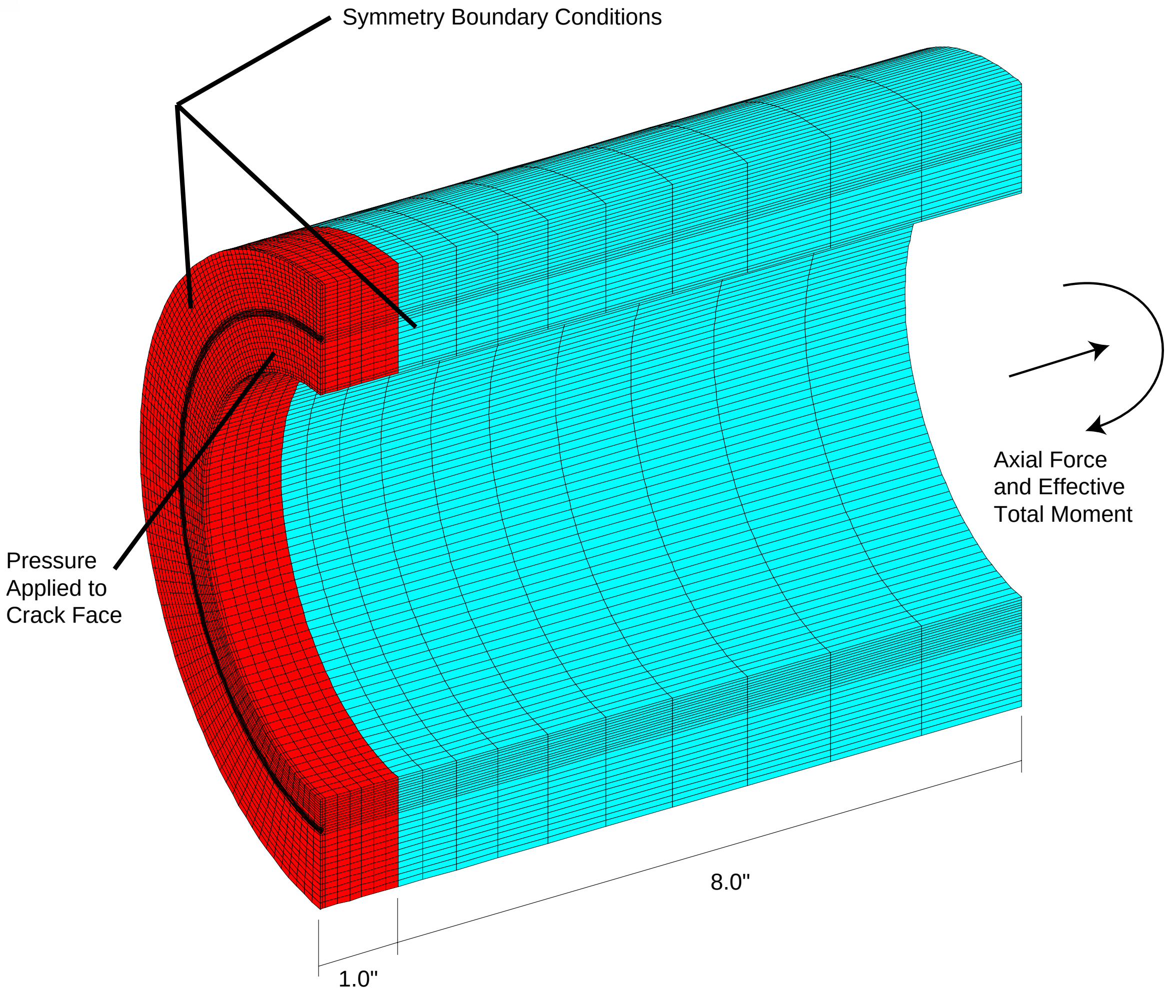
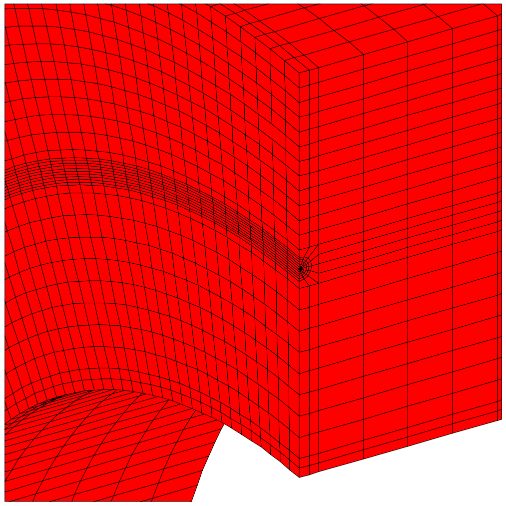
Crack Growth Modeling
Topics

- Approach
- Phase I Crack Growth Calculations
- Stress Intensity Factor Verification
- Crack Growth Convergence Checks
- Duane Arnold Consistency Check

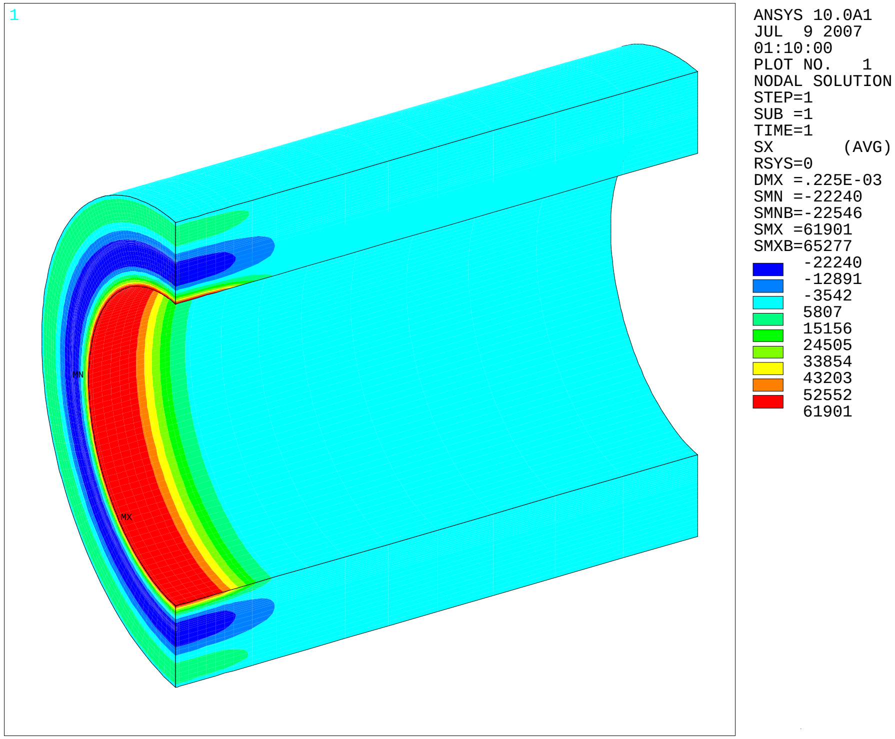
Crack Growth Modeling Approach
Cylindrical Model



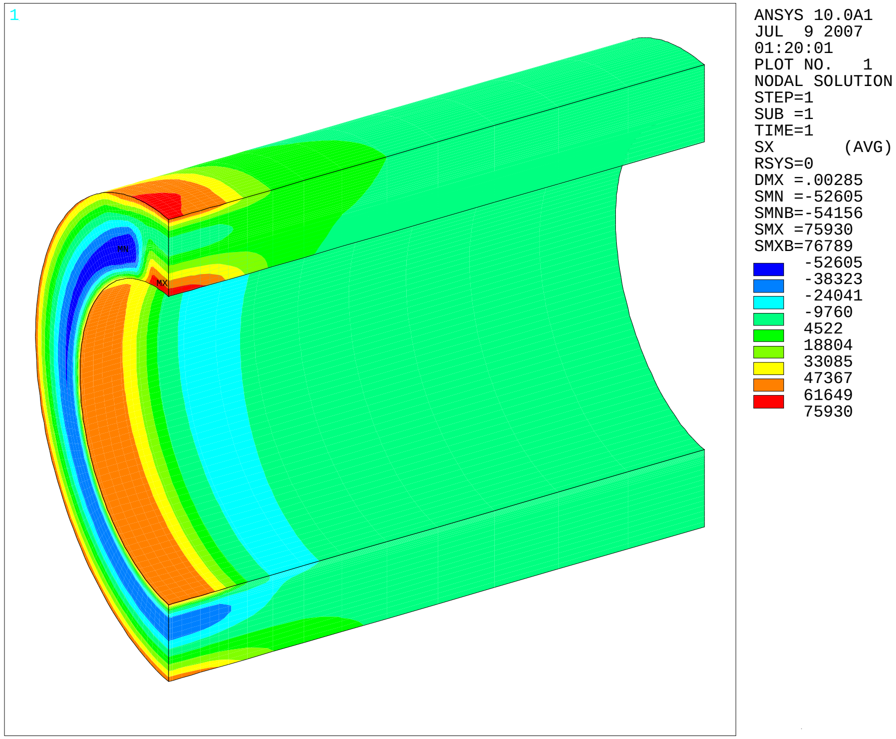


Crack Growth Modeling Approach

Cylindrical Model: Temperature Simulation of WRS



Example of Axisymmetric
WRS Simulation



Example of Circumferentially
Varying WRS Simulation

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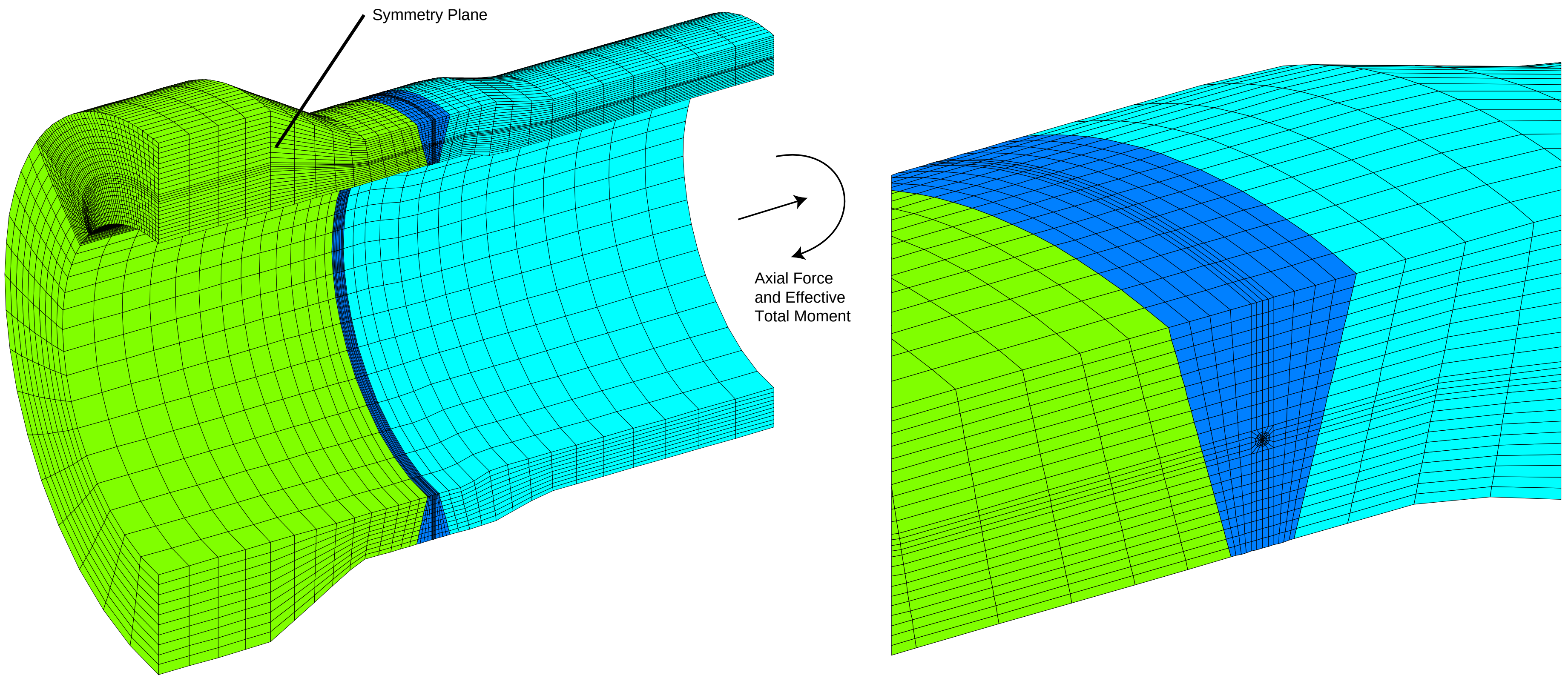
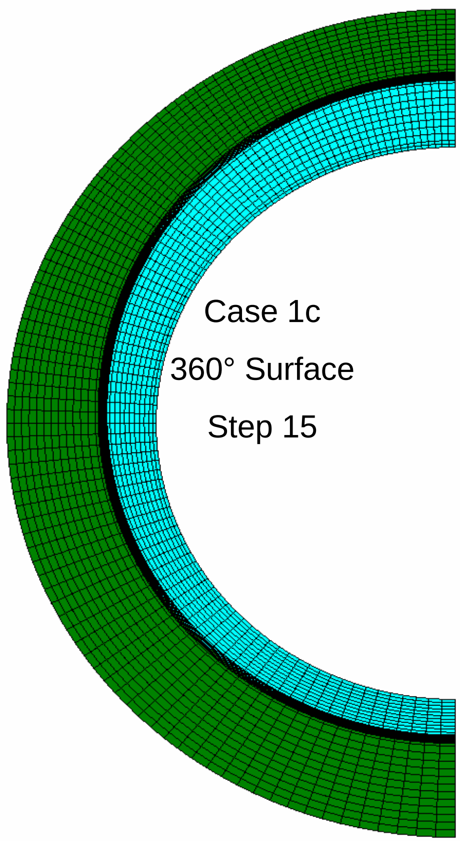
Crack Growth Modeling Approach

Nozzle-to-Safe-End Model (Type 8 Surge Nozzle)



Crack Growth Modeling Approach

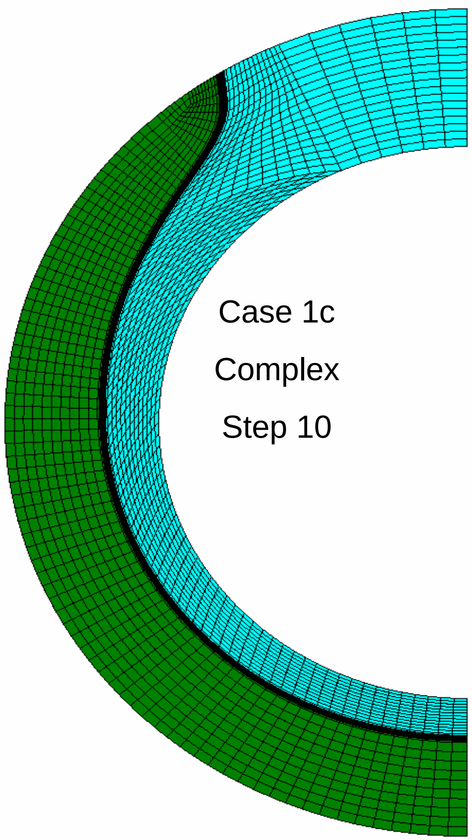
Example FEACrack Meshes



Safety and Relief Case

from 360° 10%TW surface crack

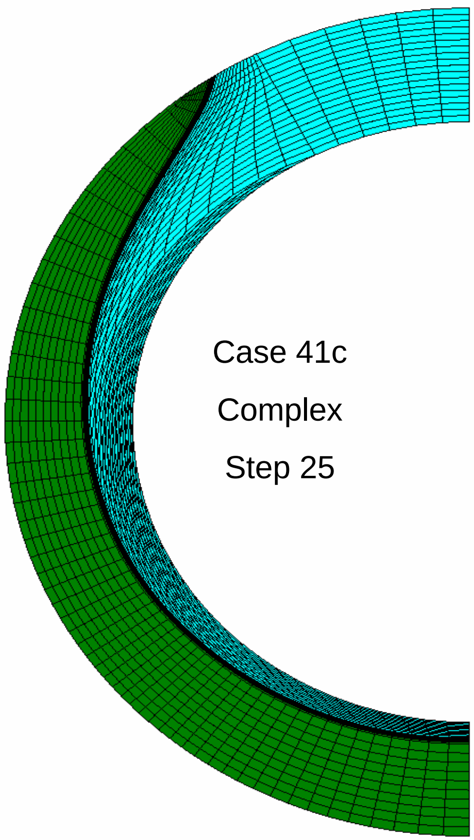
Axisymmetric WRS



Safety and Relief Case

from 360° 10%TW surface crack

Axisymmetric WRS



Safety and Relief Case

from 21:1, 40%TW surface crack

Axisymmetric WRS

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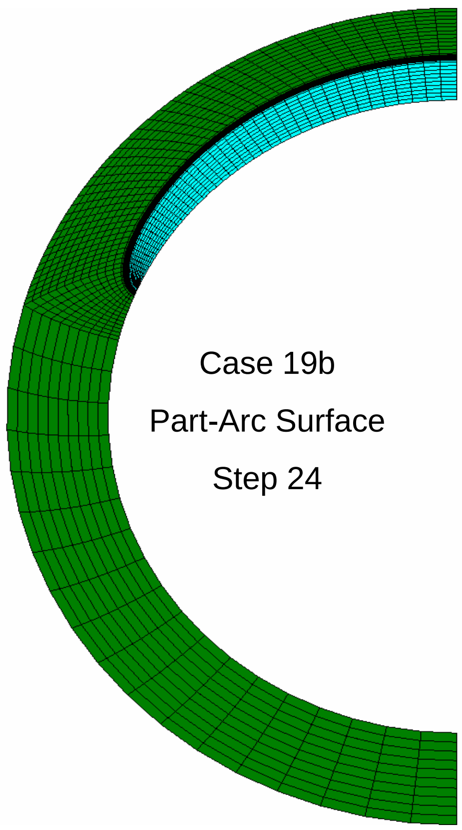
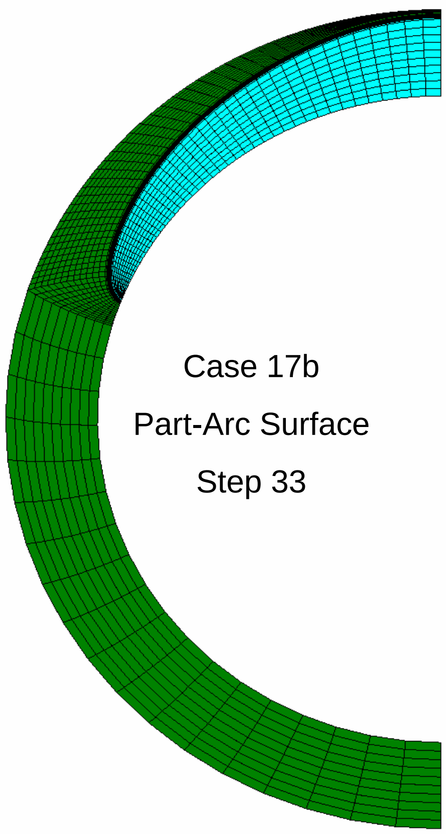
Crack Growth Modeling Approach
Example FEACrack Meshes (cont'd)



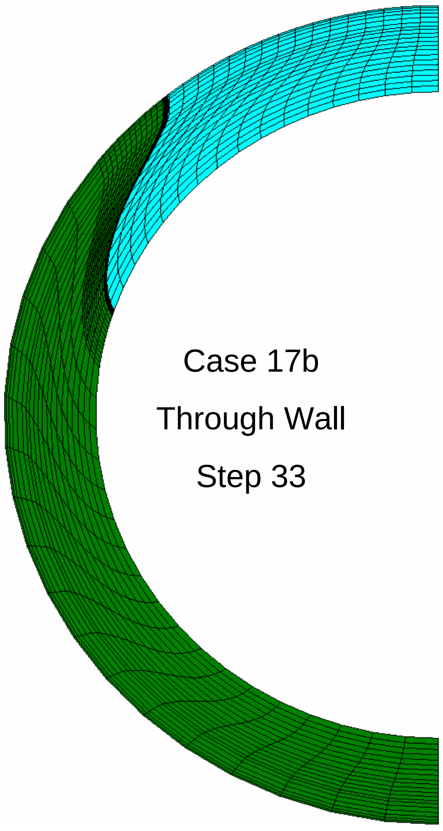
Surge Case

w/ SS Weld, Axisymmetric WRS



Surge Case

w/o SS Weld, Axisymmetric WRS



Surge Case

w/o SS Weld, Axisymmetric WRS

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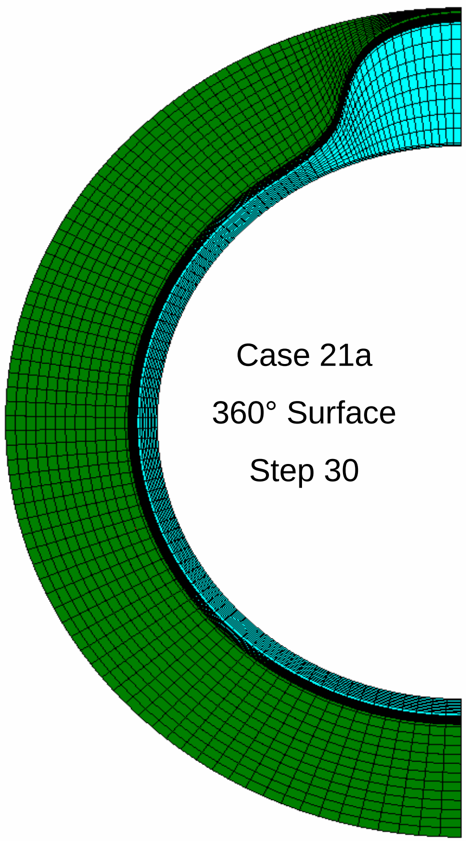
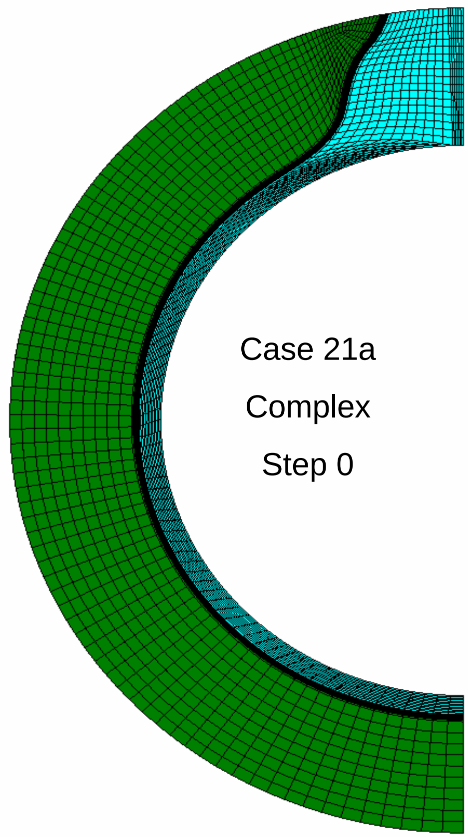
Example FEACrack Meshes (cont'd)

Crack Growth Modeling Approach



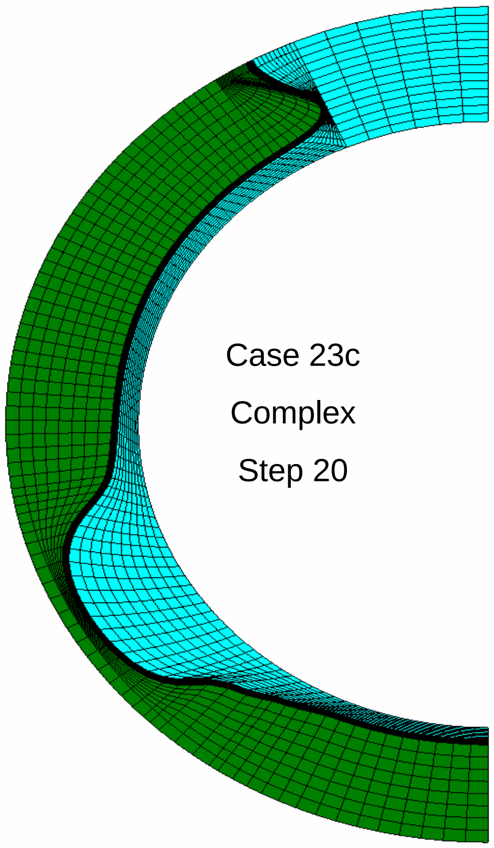
20° ID Repair Case

w/o SS Weld



20° ID Repair Case

w/o SS Weld



20° ID Repair Case

Three repair zones w/o SS Weld

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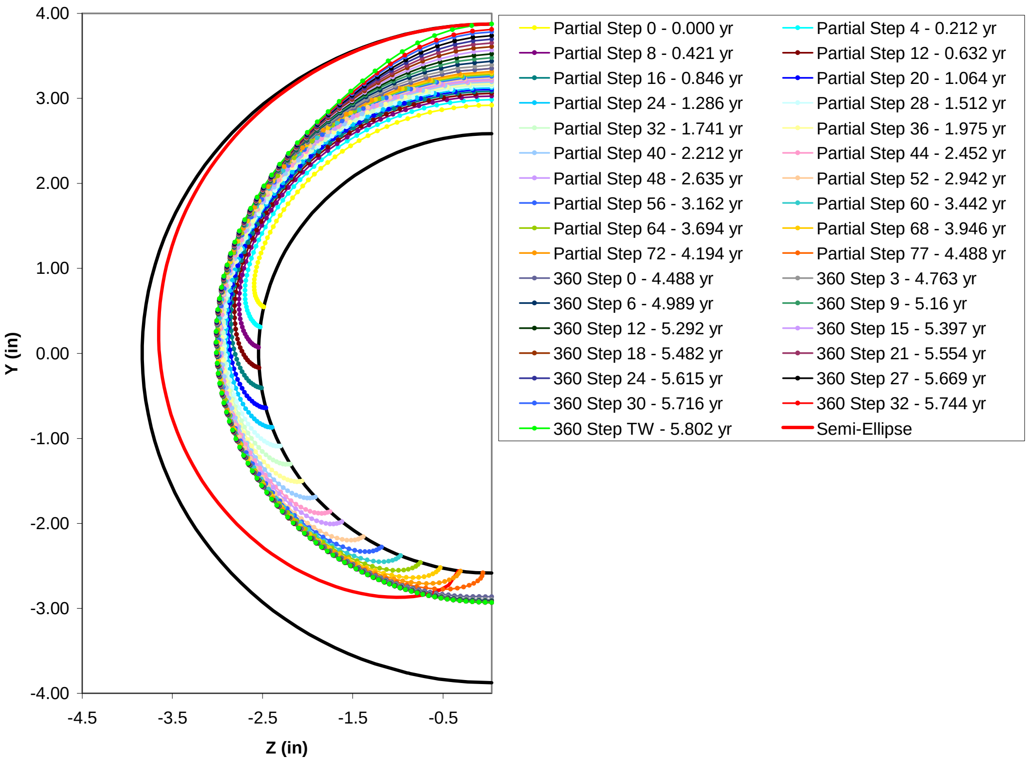
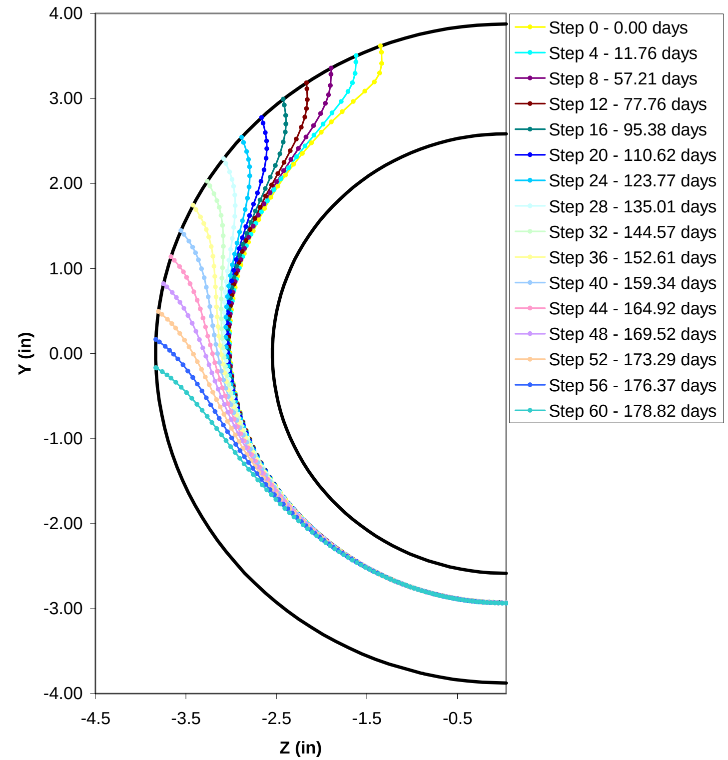
Phase I Crack Growth Calculations

Results for WC Relief Nozzle (December 2006 Inputs)



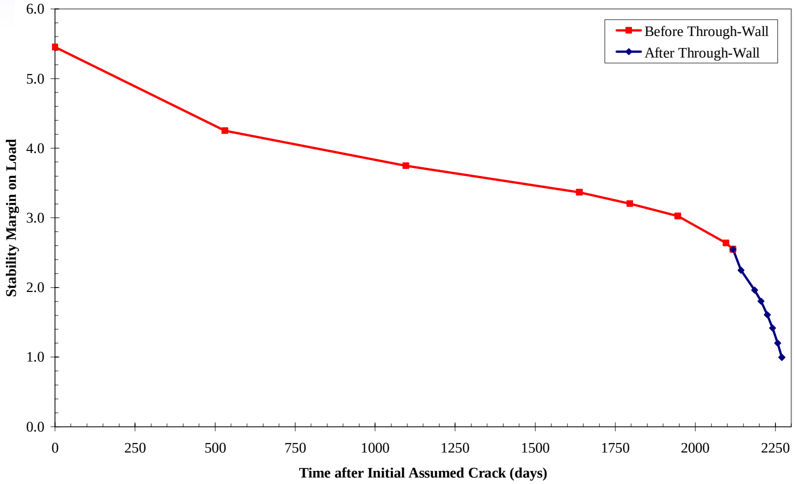
Surface Crack Progression



Complex Crack Progression

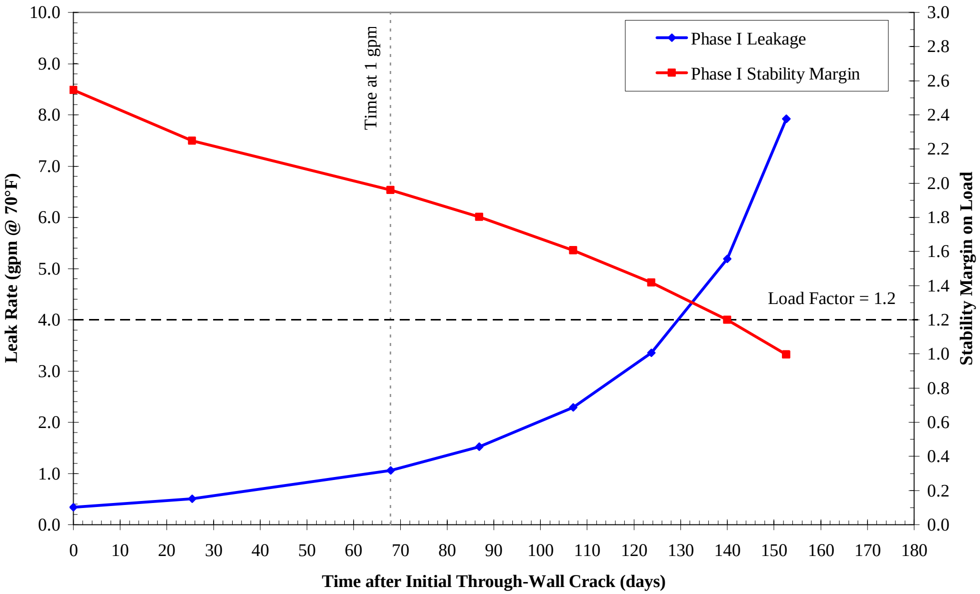
Phase I Crack Growth Calculations

Crack Stability and Leak Rate Results



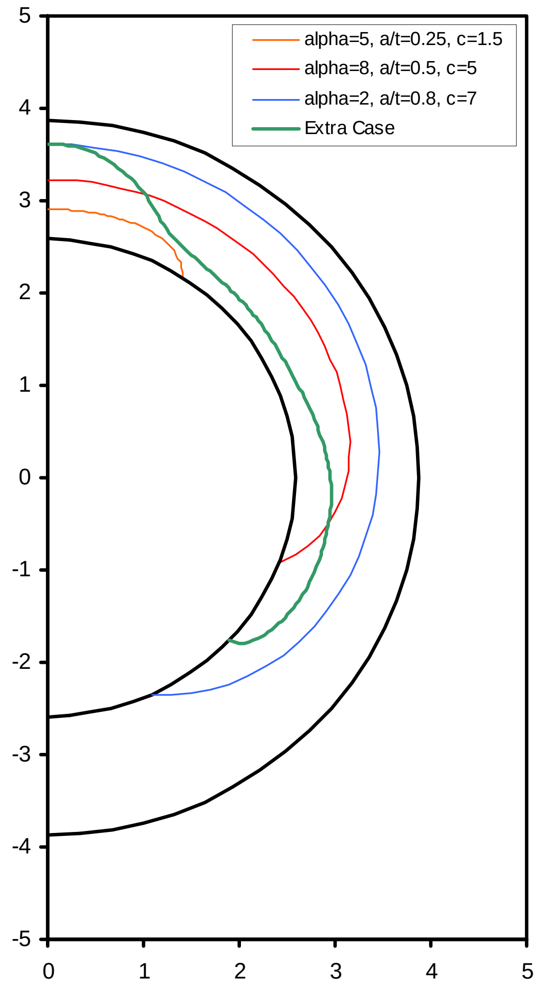
Complete Crack
Stability Development

Stability and Leak Rate
Trends for Complex Crack

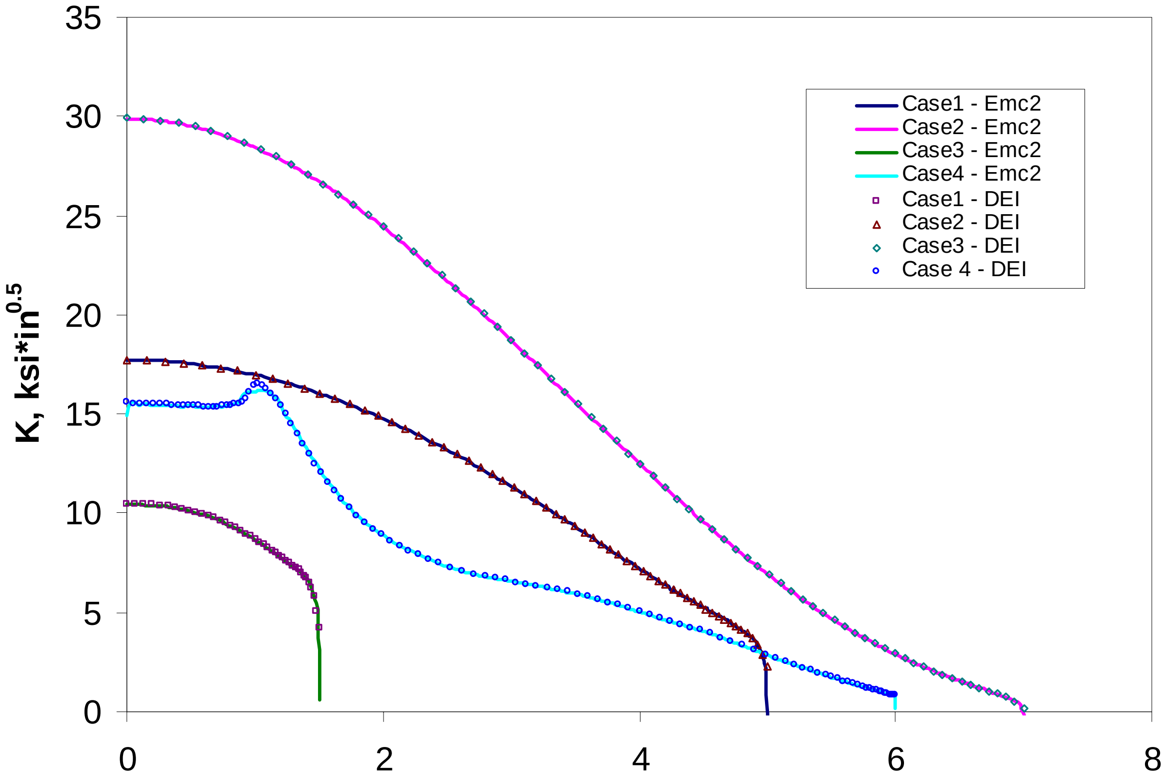


Stress Intensity Factor Verification

Comparison of DEI and EMC2 Results for Analytical Cracks



Assumed Nonstandard Crack Profiles



Comparison of DEI and EMC2 Results Showing Close Agreement Using Independent Software Models

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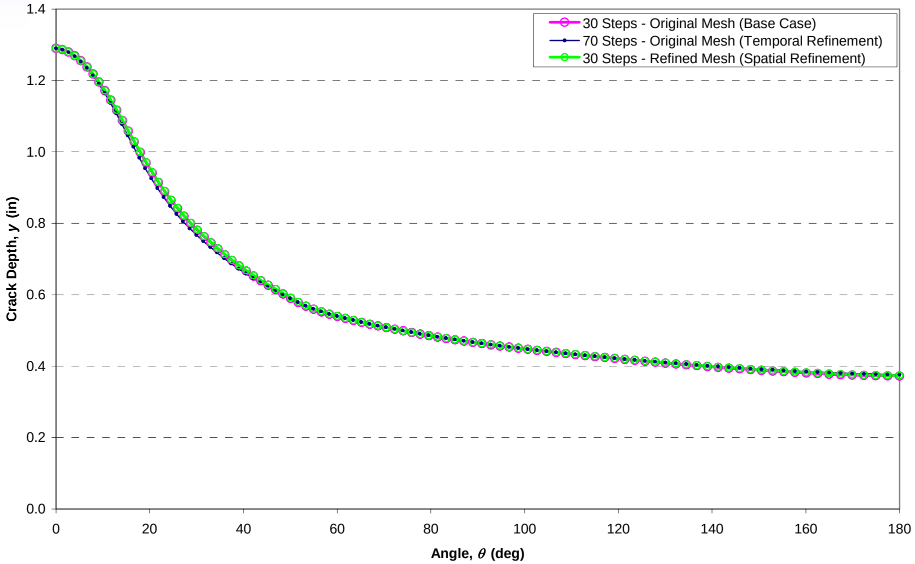
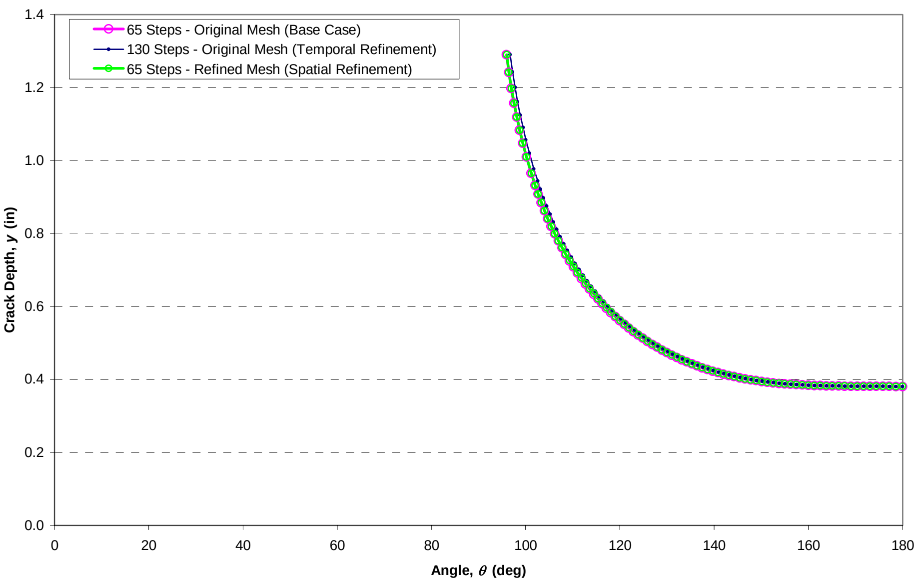
Crack Growth Convergence Checks

Temporal and Spatial Checks Demonstrating Convergence



Surface Crack Growth Progression Starting from Identical Initial Surface Flaw (Case 1c)

Complex Crack Growth Progression Starting from Identical Initial Complex Flaw (Case 1c)



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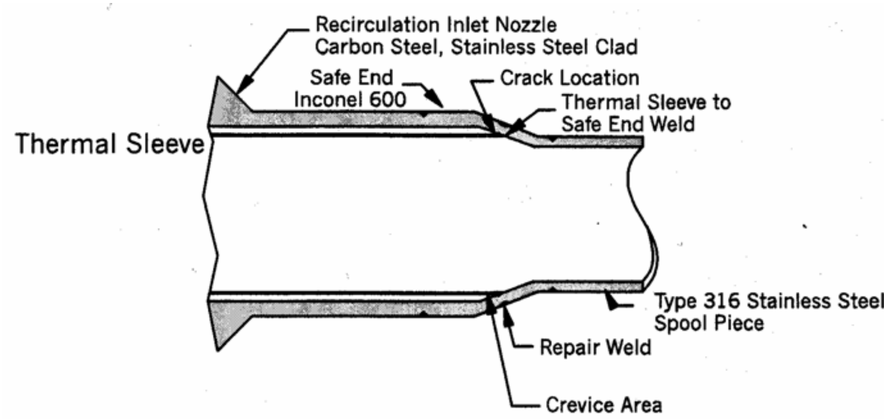
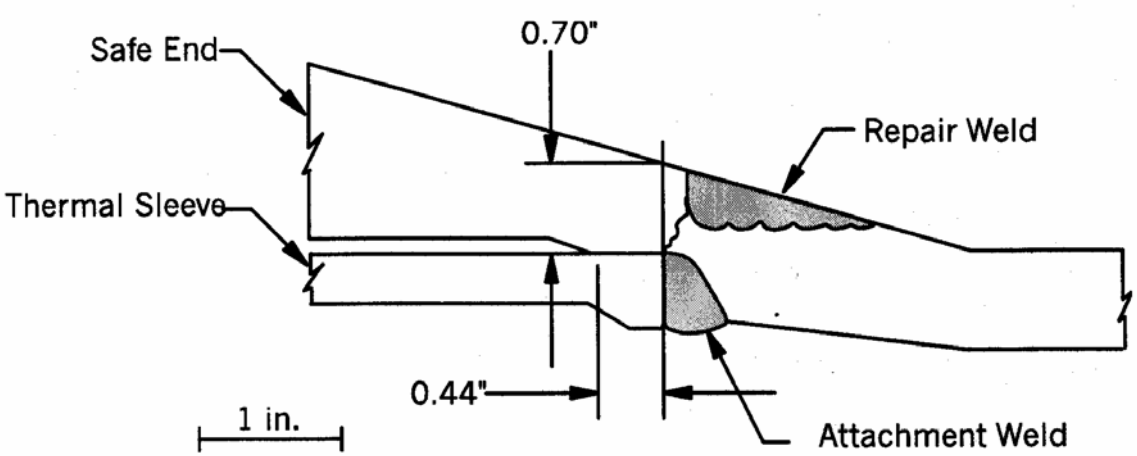
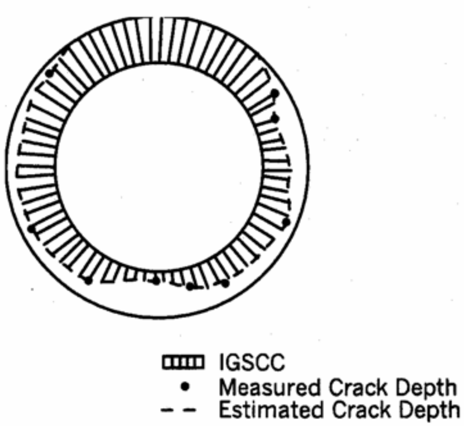
Duane Arnold Consistency Check

Duane Arnold Circumferential Crack

- The Duane Arnold crack was applied as a consistency check
  - *From MRP-113:* Crack initiation and growth were attributed to the presence of a fully circumferential crevice that led to development of an acidic environment because of the oxygen in the normal BWR water chemistry, combined with high residual and applied stresses as a result of the geometry and nearby welds. The water chemistry conditions that contributed to cracking at Duane Arnold do not exist for the case of Alloy 82/182 butt welds in PWR plants.







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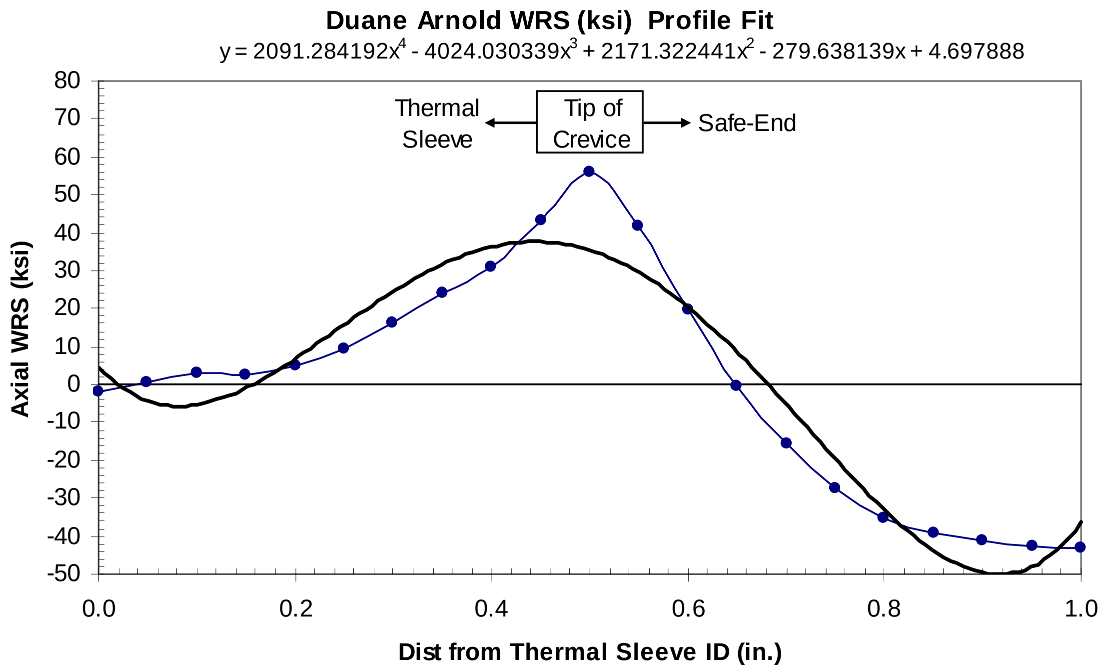
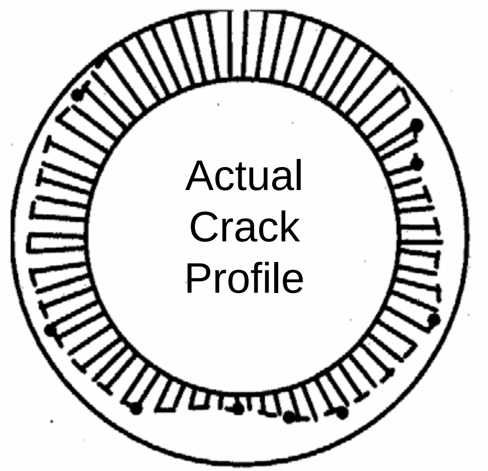
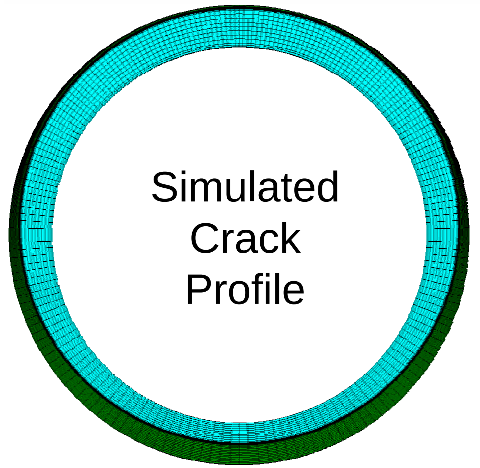
Duane Arnold Consistency Check (cont'd)

Calculated WRS Profile and Simulated Crack Profile







Assumes Initial 30% TW 360° Surface Flaw

Critical Crack Size Calculations
Topics

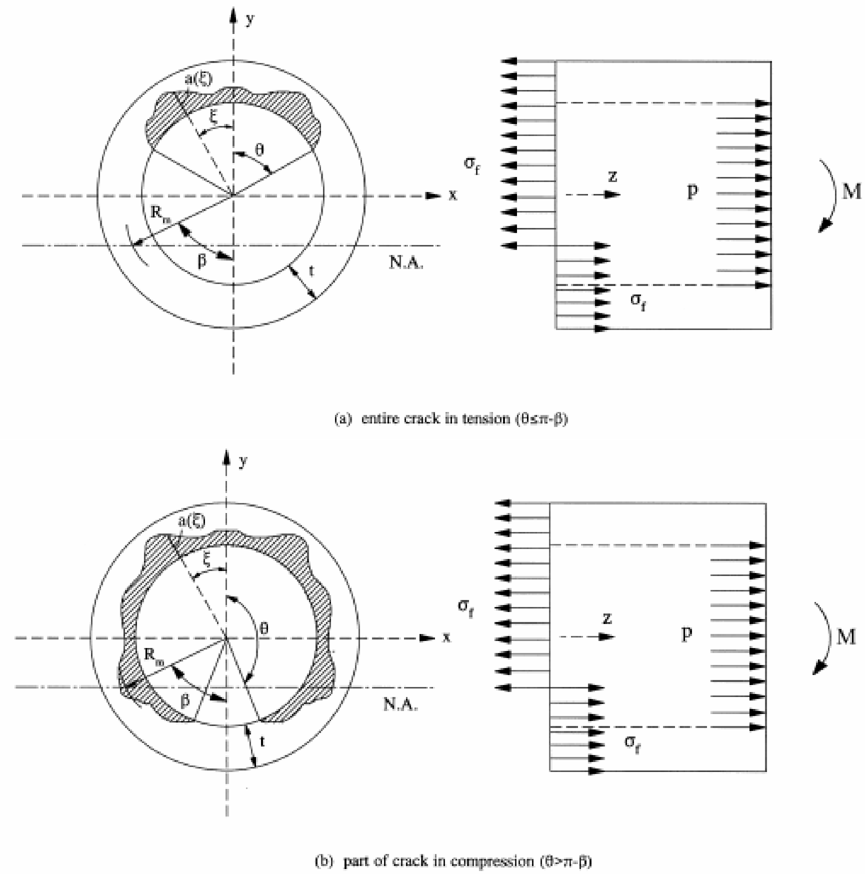
- Approach
- Treatment of Secondary Loads
- EPFM Considerations
- Verification
- Validation vs. Experiment

Critical Crack Size Calculations
Approach

- The flow strength for net section collapse (NSC) based on the safe end material tensile properties
- NSC equations developed by Rahman and Wilkowski were used to calculate critical crack size for an arbitrary crack shape
  - Spreadsheet calculation was verified against Arbitrary Net Section Collapse (ANSC) software developed by Structural Integrity Associates
- Full normal thermal stress used to calculate the critical crack size
  - Full scale SS and Alloy 600 pipe tests and piping system FEA compliance studies support reduced thermal loads prior to collapse
- Applied Z-factor to reduce supportable moment to consider effect of EPFM failure mechanism
  - Full scale SS and Alloy 600 pipe tests support limit load failure mechanism
  - Comparison of J-R curve fracture toughness demonstrates Alloy 182 weld metal is similar to the pipe test materials
- Critical load for various calculated crack growth progressions checked against reported operating load to determine load margin factor vs. time

Critical Crack Size Calculations
Force and Moment Equilibrium for Arbitrary Crack

- Rahman and Wilkowski have published the thin-wall solution for axial force and applied moment equilibrium given a circumferential flaw with arbitrary depth profile
- DEI implemented this solution in spreadsheet form
- The solution was applied to crack profiles calculated by the FEACrack software
  - Case 1: Entire crack in tension
  - Case 2a: Part of crack in compression zone with crack taking compression
  - Case 2b: Part of crack in compression zone with crack not taking compression
- Arbitrary Net Section Collapse (ANSC) software by Structural Integrity Associates used to validate spreadsheet calculation
  - ANSC also allows arbitrary moment direction, unlike Rahman and Wilkowski



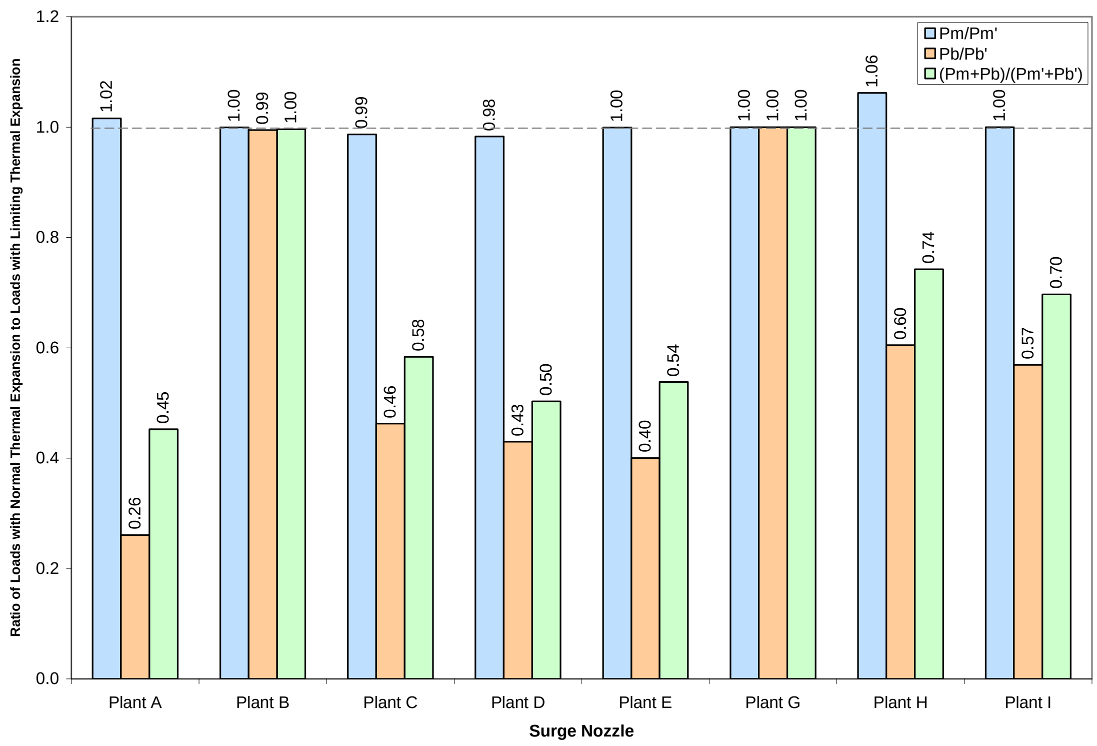
S. Rahman and G. Wilkowski, "Net-Section-Collapse Analysis of Circumferentially Cracked Cylinders—Part I: Arbitrary-Shaped Cracks and Generalized Equations," *Engineering Fracture Mechanics*, Vol. 61, pp. 191-211, 1998.

Critical Crack Size Calculations
Treatment of Loads

- These types of loads are included in the net section collapse calculation:
  - Internal pressure (including on crack face)
  - Dead weight
  - Normal pipe thermal expansion
- These types of loads are not included:
  - Welding residual stress
  - Effect of thermal stratification for surge nozzles
  - Local thermal stress due to differential thermal expansion (Q-stress), including due to plant transients
  - Seismic loads
  - Safety and relief valve discharge loads
  - LOCA loads

Critical Crack Size Calculations
Effect of Thermal Stratification on Surge Nozzle Loads

- Crack growth matrix results showed that surge nozzles with fill-in welds and relatively high bending moment are the limiting cases (Plants B and G)
- For these two plants, the normal thermal load bounds all thermal stratification effects



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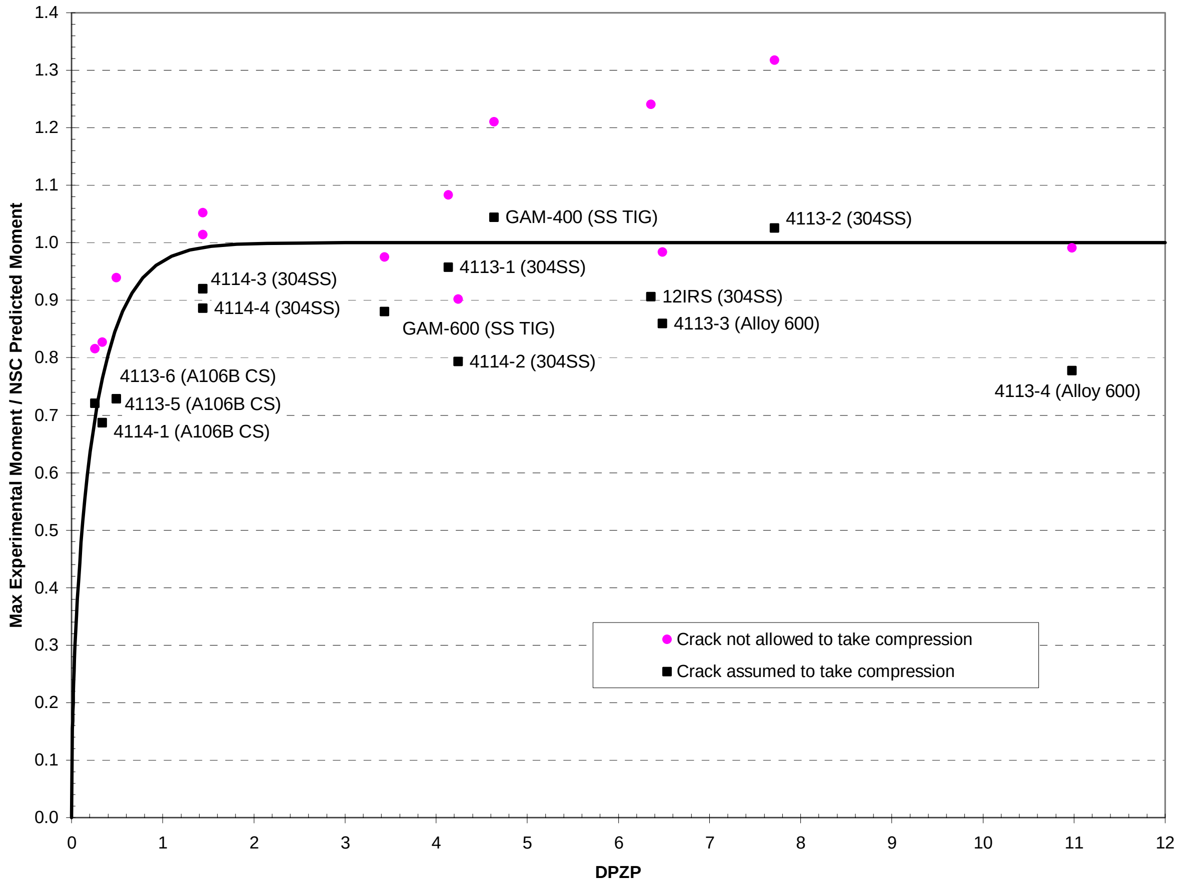
Critical Crack Size Calculations
Effect of Plant Shutdown/Startup and Reactor Trip Transients

- Plant shutdown/startup and reactor trip transients have the following effects:
  - Increased thermal stratification magnitude (surge line only)
  - Local secondary stress effects, such as through-wall and axial thermal gradient effects
- Thermal stratification effects on the surge line are not included in the crack stability calculations on the basis of full-scale pipe tests and piping system compliance studies (Appendices B and C of MRP-216) that support full relief of thermal pipe expansion loads for the surge nozzles
- Local secondary stress effects are relieved prior to rupture for Alloy 82/182 weld material
- In addition, any plant shutdown/startup or reactor trip transients prior to the originally scheduled spring 2008 refueling outage do not affect the crack stability margin because crack growth via a single fatigue cycle is negligible
  - Crack growth is driven by PWSCC during steady operation at full temperature

Critical Crack Size Calculations
Validation vs. Experiment

- Experimental failure loads for similar materials support conclusion that approach taken is conservative



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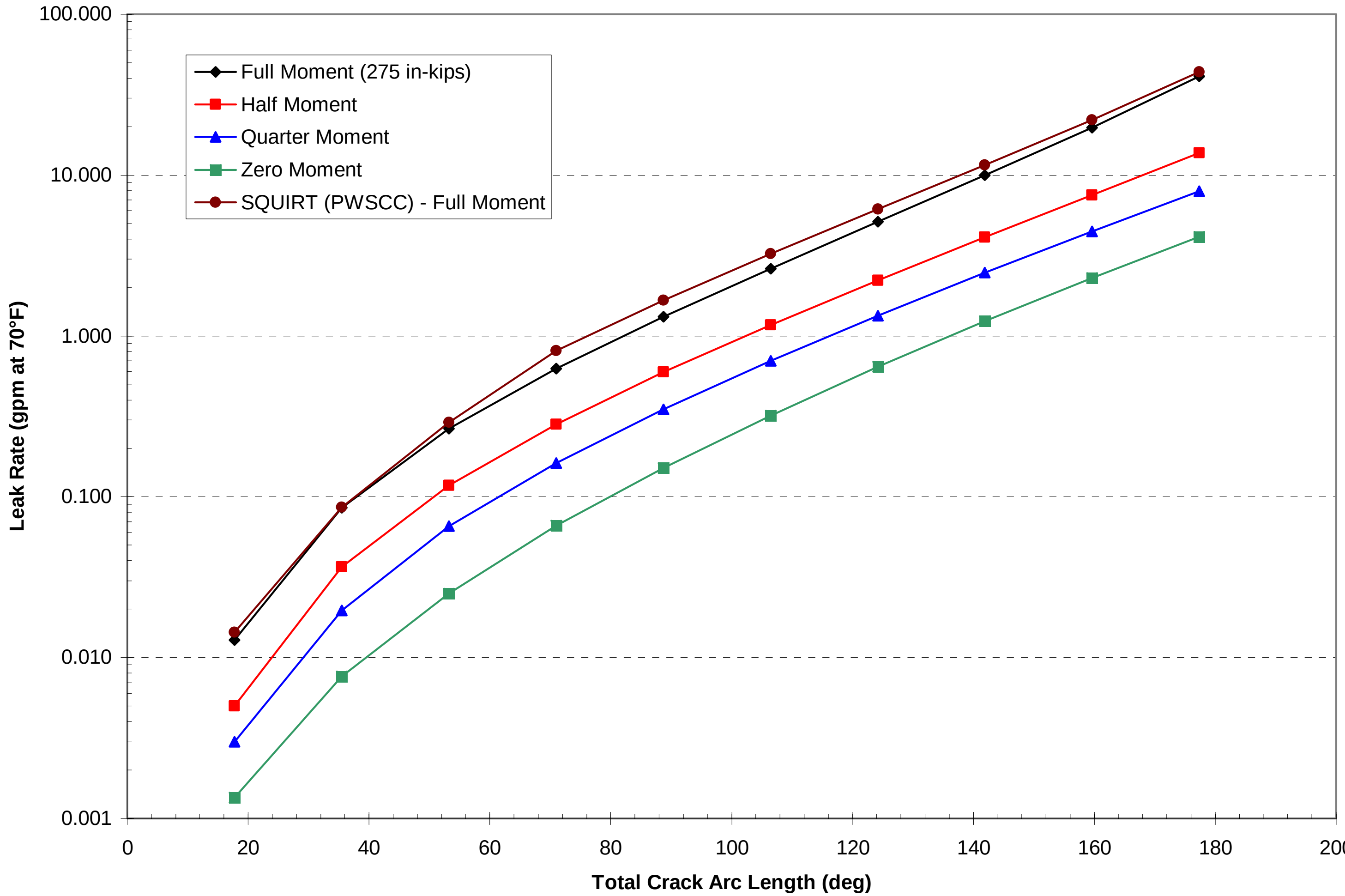
Leak Rate Modeling
Summary

- Leak rate calculations using two standard industry codes
  - PICEP and SQUIRT
- Flow rate through the crack based on PWSCC morphology
- Leak rate calculations based on crack opening displacement (COD) from FEA rather than standard COD expressions for simplified loading assumption

Leak Rate Modeling

Scoping Results Based on WC Relief Nozzle DM Weld Dimensions and COD Calculated by PICEP and SQUIRT



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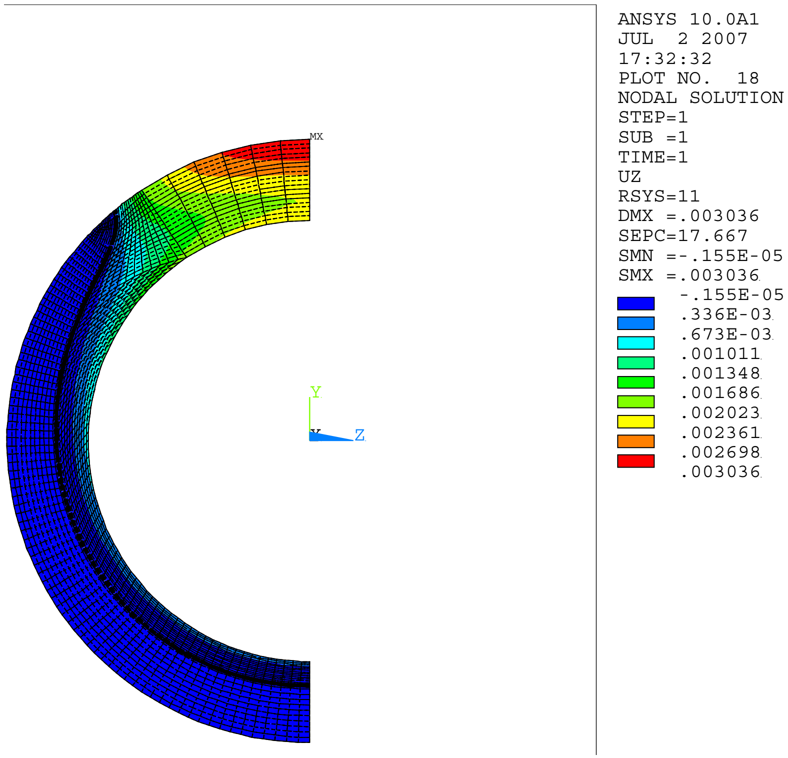
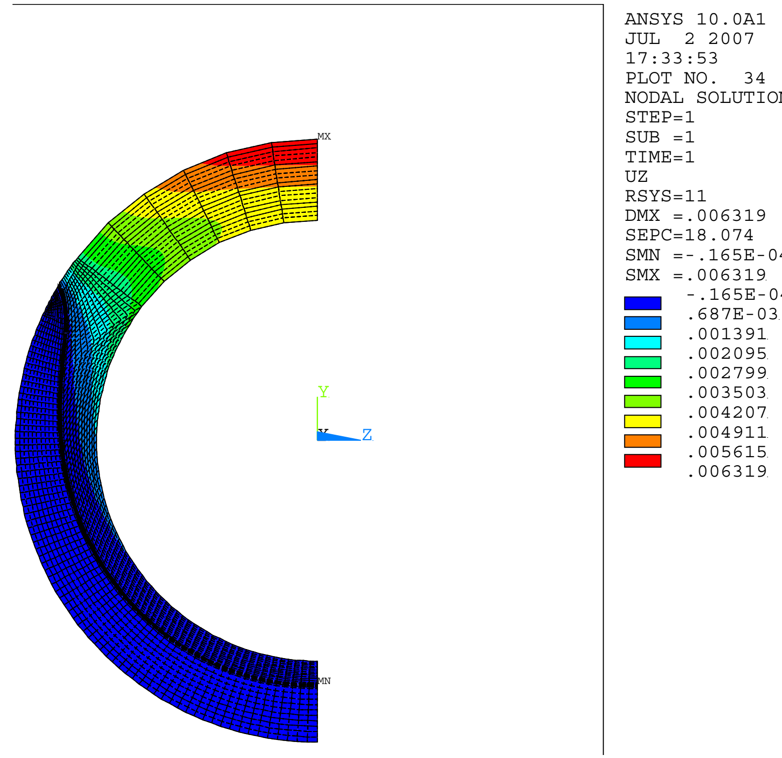
Leak Rate Modeling

Example Crack Opening Displacements (Half COD)



Case 12 – 1 gpm leak rate



Case 12 – Stability Load Margin Factor = 1.2

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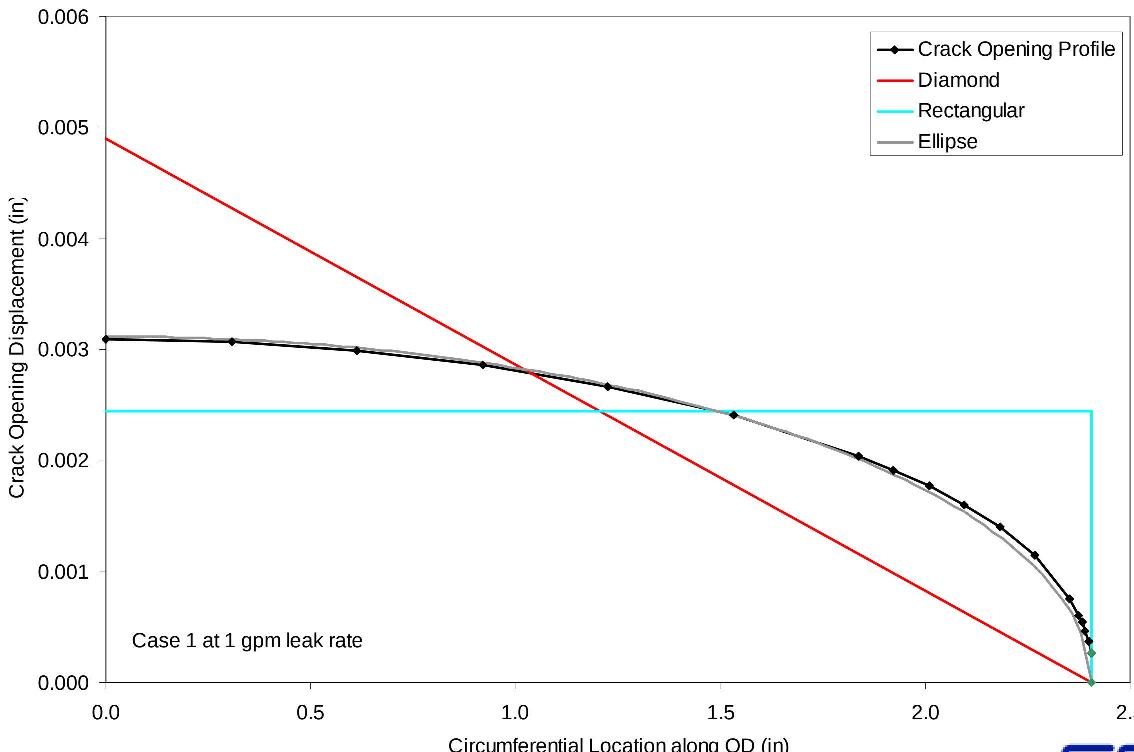
Leak Rate Modeling

Effect of Assumed Crack Shape on Calculated Leak Rate

- Crack opening at OD from FEA closely approximated by ellipse
- Ellipse selected as default crack shape
- Rectangular and diamond crack shapes both resulted in 2% increase in predicted leak rate for the same crack opening area



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Sensitivity Case Matrix
Topics

- Evaluation Criteria
- Sensitivity Parameters
- Definition of Case Matrix
- Matrix Results
- Matrix Conclusions

Sensitivity Case Matrix

Evaluation Criteria

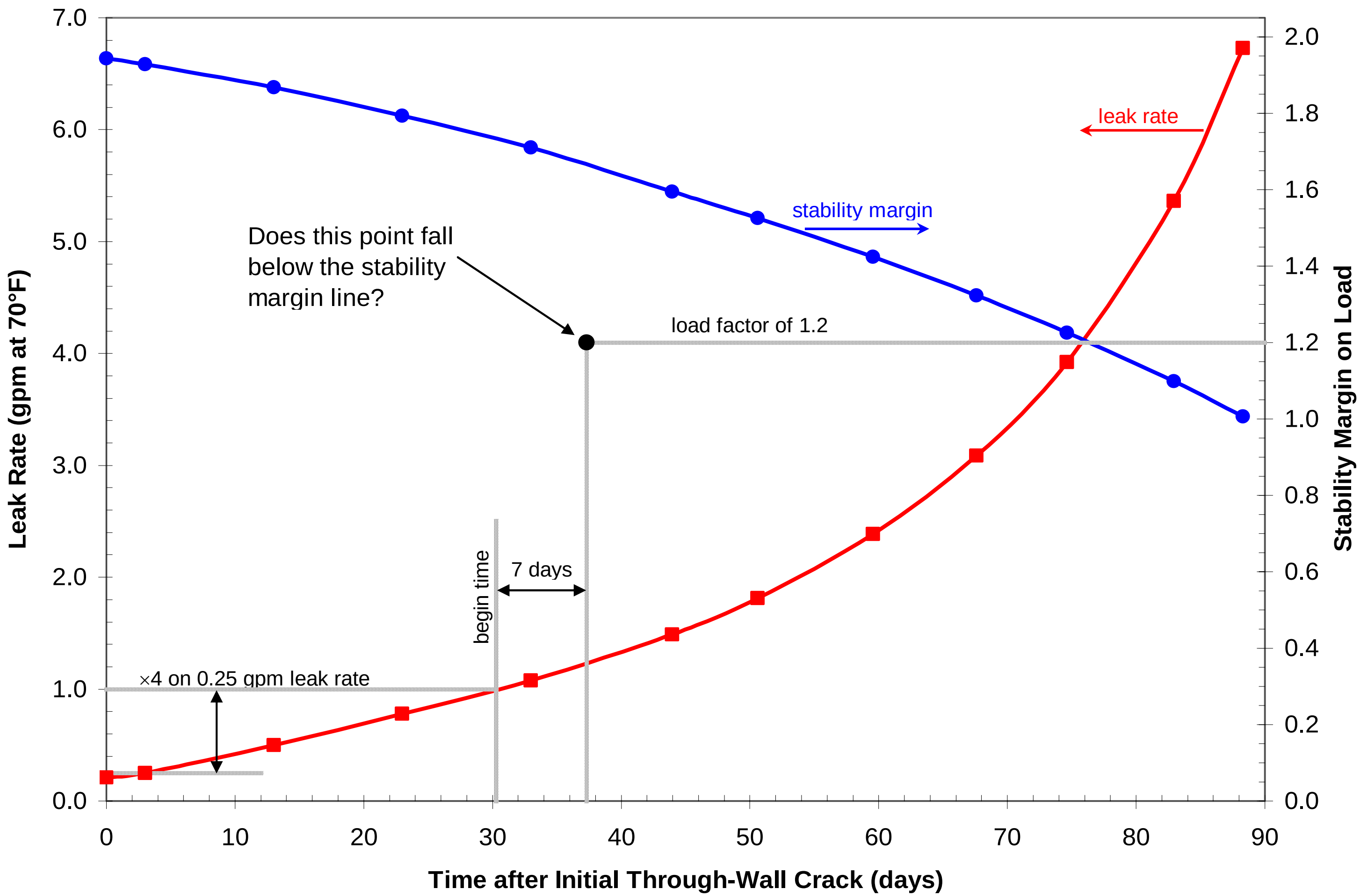

Illustration of Approach for Hypothetical Leakage and Stability Data

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Sensitivity Case Matrix
Sensitivity Parameters

- Fracture Mechanics Model Type
  - Cylindrical
  - Nozzle-to-Safe-End
- Plant Specific Geometries
- Plant Specific Piping Loads
- Welding Residual Stresses
  - Axisymmetric
  - ID Weld Repair
- Crack Growth Rate Equation
- Initial Flaw Geometry
- Effect of Multiple Crack Initiation Sites

Sensitivity Case Matrix
Crack Growth Rate Equation

- Sensitivity cases examine the effect of main uncertainties in the MRP-115 Crack Growth Rate (CGR) equation:
  - Uncertainty in the K_I power-law exponent (nominal 1.6) addressed by crack growth sensitivity cases assuming 5th and 95th percentile exponent values from MRP-115 statistical fit to laboratory CGR data
    - Power-law constant adjusted for these sensitivity cases to maintain 75th percentile value used for MRP-115 deterministic equation
  - Uncertainty in power-law constant itself addressed simply by scaling factor on time
    - 95th percentile constant is 1.77 times 75th percentile constant value
- No credit taken for a PWSCC crack growth K_I threshold

Sensitivity Case Matrix
Initial Flaw Geometry

- Sensitivity cases investigate the effect of initial flaw geometry
  - Initial depth
  - Initial aspect ratio (2c/a) or 360° uniform depth surface flaw
  - Initial shape factor (e.g., low shape factor to semi-ellipse to uniform depth)
- Sensitivity cases indicate that crack profile upon through-wall penetration (or upon crack arrest) is insensitive to initial flaw shape for a given aspect ratio and depth.

Sensitivity Case Matrix
Effect of Multiple Crack Initiation Sites

- Sensitivity cases investigate the effect of multiple crack initiation (e.g., Wolf Creek surge nozzle NDE results)
  - Enveloping of multiple initial flaws with one modeled flaw
  - Modeling of a part-depth 360° flaw
  - Growing multiple individual flaws and then combining on a single weld cross section for stability calculation

Sensitivity Case Matrix
Definition of Case Matrix

- Up to three WRS profiles applied to each case
  - Geometry and load base cases (1-20)
    - Axisymmetric WRS
    - Moment load varied up to maximum reported for specific configuration
  - ID repair base cases (21-26)
    - Non-axisymmetric WRS based on ID repair WRS FEA
  - Further bending moment sensitivity cases (27-30)
  - Sensitivity cases to investigate potential uncertainty in as-built dimensions (31-32)
    - Hypothetical ±10% variation in weld thickness
  - Axial membrane load sensitivity cases (33-34)
    - Relatively narrow range in membrane load for each geometry
  - Effect of length over which thermal strain simulating WRS is applied (35)

Sensitivity Case Matrix
Definition of Case Matrix (cont'd)

- Simulation of elastic-plastic redistribution of stress at ID (36)
- Effect of initial crack shape and depth (37-41)
- Effect of stress intensity factor dependence of crack growth rate equation (42-47)
  - 5^{th} percentile exponent of 1.0 or 95^{th} percentile exponent of 2.2 assumed
- Effect of pressure drop along leaking crack (48)
  - Other cases assume full primary pressure applies to leaking crack face
- Effect of relaxation of normal operating thermal load (49-51)
  - For through-wall portion of crack growth progression, the normal thermal load has been eliminated for these sensitivity cases (for crack growth, leak rate, and critical crack size calculations)
- Effect of nozzle-to-safe-end crack growth model vs. standard cylindrical crack growth model (52-53)
  - Investigate effect of detailed geometry
- Supplementary cases specific to effect of multiple flaws on limiting surge nozzles (S1-S9)

Matrix Results
Sensitivity Summary

Case #	WRS Subcase	Base Case	Qualitative Sensitivity Description	Quantitative Sensitivity Description	Result Comparison: Time Interval from 1 gpm to a Stability Margin Factor of 1.2 [days]		Stability Margin Factor at 1 gpm (or at initial leak rate if higher)		Calculated Leak Rate (at 70°F) at a Stability Margin Factor of 1.2 [gpm]	
					from	*to*	*from*	*to*	*from*	*to*
2	c	1c	Case 1c with intermediate bending moment	Pb *from* 5.71 ksi *to* 5.30 ksi	109	118	2.24	2.31	5.81	5.89
3	c	1c	Case 1c with low bending moment	Pb *from* 5.71 ksi *to* 4.88 ksi	109	125	2.24	2.40	5.81	6.22
5	c	4c	Case 4c with low bending moment	Pb *from* 5.74 ksi *to* 4.88 ksi	112	137	2.18	2.35	5.22	5.81
7	c	6c	Case 6c with low bending moment	Pb *from* 7.63 ksi *to* 4.78 ksi	41	71	1.70	2.01	4.04	5.44
9	c	8c	Case 8c with low bending moment	Pb *from* 6.70 ksi *to* 4.88 ksi	99	144	2.14	2.50	5.58	6.56
11	c	10c	Case 10c with low bending moment	Pb *from* 4.89 ksi *to* 4.50 ksi	73	73	2.07	2.08	3.81	3.70
13	c	12c	Case 12c with low bending moment	Pb *from* 4.75 ksi *to* 4.13 ksi	48	54	1.86	1.94	3.54	3.49
16	c	15c	Case 15c with low bending moment	Pb *from* 4.65 ksi *to* 4.13 ksi	*arrest*	*arrest*	*arrest*	*arrest*	*arrest*	*arrest*
17	b	17a	Case 17a with shifted weld residual stress	WRS *from* w/ SS weld *to* w/o SS weld	*arrest*	35	*arrest*	1.71	*arrest*	69.28
18	a	17a	Case 17a with low bending moment	Pb *from* 13.57 ksi *to* 4.88 ksi	*arrest*	*arrest*	*arrest*	*arrest*	*arrest*	*arrest*
18	b	17b	Case 17b with low bending moment	Pb *from* 13.57 ksi *to* 4.88 ksi	35	43	1.71	1.79	69.28	15.79
20	b	19b	Case 19b with low bending moment	Pb *from* 14.55 ksi *to* 6.65 ksi	*arrest*	*arrest*	*arrest*	*arrest*	*arrest*	*arrest*
21	a	1c	Case 1c with a 20° ID repair (WRS w/o SS weld)	WRS *from* ASME 3/30 fit *to* 20° ID repair w/o SS weld	109	>>21	2.24	4.42	5.81	1.28 (note 1)
22	a	3c	Case 3c with a 20° ID repair (WRS w/o SS weld)	WRS *from* ASME 3/30 fit *to* 20° ID repair w/o SS weld	125	>>17	2.40	4.78	6.22	1.25 (note 1)
23	a	6c	Case 6c with a 20° ID repair (WRS w/o SS weld)	WRS *from* ASME 3/30 fit *to* 20° ID repair w/o SS weld	41	>>37	1.70	3.36	4.04	1.67 (note 1)
23	b	6c	Case 6c with a 20° ID repair (modified ASME WRS)	WRS *from* ASME 3/30 fit *to* 20° ID repair modified ASME	41	173	1.70	2.98	4.04	6.44
23	c	6c	Case 6c with a 20° ID repair (WRS w/o SS weld) and multiple repairs	WRS *from* ASME 3/30 fit *to* 20° ID repair w/o SS weld; Number of Repairs *from* 1 *to* 3	41	>>21	1.70	2.99	4.04	1.22 (note 1)
24	a	7c	Case 7c with a 20° ID repair (WRS w/o SS weld)	WRS *from* ASME 3/30 fit *to* 20° ID repair w/o SS weld	71	>>21	2.01	4.24	5.44	1.31 (note 1)
25	a	17a	Case 17a with an ID repair (WRS w/ SS weld)	WRS *from* w/ SS weld *to* ID repair w/ SS weld	*arrest*	78	*arrest*	2.12	*arrest*	98.51
25	b	17b	Case 17b with an ID repair (WRS w/o SS weld)	WRS *from* w/o SS weld *to* ID repair w/o SS weld	35	68	1.71	2.05	69.28	91.86
26	a	18a	Case 18a with an ID repair (WRS w/ SS weld)	WRS *from* w/ SS weld *to* ID repair w/ SS weld	*arrest*	>>40	*arrest*	2.83	*arrest*	5.40 (note 1)
27	b	17b	Case 17b with intermediate bending moment	Pb *from* 13.57 ksi *to* 13.00 ksi	35	38	1.71	1.74	69.28	70.43
28	b	17b	Case 17b with low bending moment	Pb *from* 13.57 ksi *to* 10.00 ksi	35	27	1.71	1.67	69.28	28.75
29	b	18b	Case 18b with high bending moment	Pb *from* 4.88 ksi *to* 7.00 ksi	43	11	1.79	1.38	15.79	8.49
30	b	18b	Case 18b with low bending moment	Pb *from* 4.88 ksi *to* 4.03 ksi	43	*arrest*	1.79	*arrest*	15.79	*arrest*
31	c	1c	Case 1c with 10% greater thickness	Thickness *from* 1.29 in *to* 1.419 in	109	146	2.24	2.46	5.81	6.43
32	c	1c	Case 1c with 10% lesser thickness	Thickness *from* 1.29 in *to* 1.161 in	109	74	2.24	1.96	5.81	4.80
33	c	4c	Case 4c with low axial membrane stiffness	Pm *from* 1.90 ksi *to* 1.64 ksi	112	123	2.18	2.20	5.22	5.27
34	c	4c	Case 4c with high axial membrane stiffness	Pm *from* 1.90 ksi *to* 2.15 ksi	112	98	2.18	2.12	5.22	5.52
35	c	6c	Case 6c with shortened weld length	Weld Length *from* 1 in *to* 0.5 in	41	32	1.70	1.62	4.04	3.67

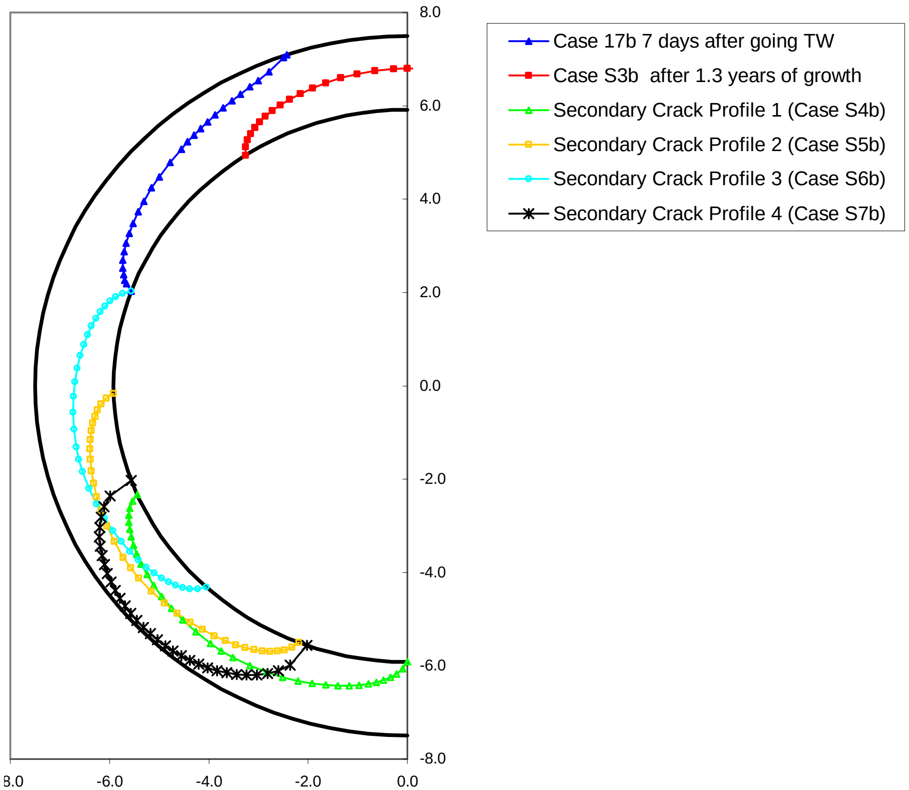
Note 1: Results not specific for a Stability Margin Factor of 1.2; case has Stability Margin Factor >> 1.2 when time > 40 days

Matrix Results
Sensitivity Summary (cont'd)

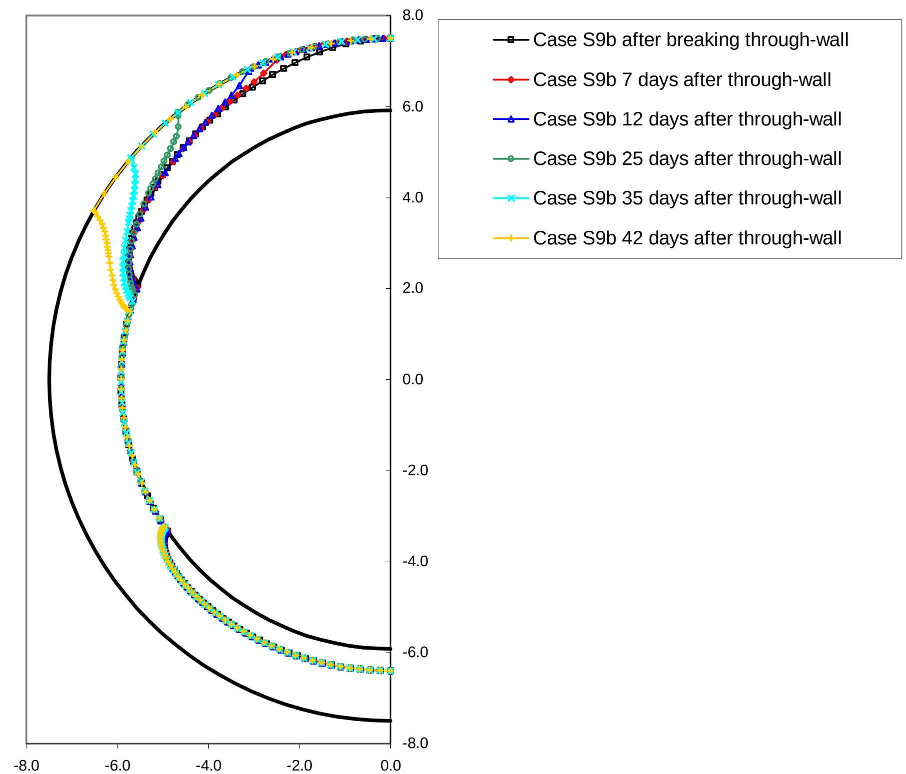
Case #	WRS Subcase	Base Case	Qualitative Sensitivity Description	Quantitative Sensitivity Description	Result Comparison: Time Interval from 1 gpm to a Stability Margin Factor of 1.2 [days]		Stability Margin Factor at 1 gpm (or at initial leak rate if higher)		Calculated Leak Rate (at 70°F) at a Stability Margin Factor of 1.2 [gpm]	
					from	*to*	*from*	*to*	*from*	*to*
36	c	6c	Case 6c modeled with plastic redistribution (modified WRS)	WRS *from* ASME 3/30 fit *to* plastic redistribution	41	42	1.70	1.69	4.04	3.99
37	c	6c	Case 6c with natural shape initial surface flaw	Initial Surface Flaw *from* Uniform, 10% TW 360° *to* 21:1, 26% TW, natural shape partial-arc	41	49	1.70	1.83	4.04	4.97
38	c	6c	Case 6c with semi-ellipse initial surface flaw	Initial Surface Flaw *from* Uniform, 10% TW 360° *to* 21:1, 26% TW, semi-ellipse partial-arc	41	49	1.70	1.83	4.04	4.98
39	c	6c	Case 6c with constant depth initial surface flaw	Initial Surface Flaw *from* Uniform, 10% TW 360° *to* 21:1, 26% TW, constant depth partial-arc	41	47	1.70	1.81	4.04	4.87
40	c	6c	Case 6c with shallow initial surface flaw	Initial Surface Flaw *from* Uniform, 10% TW 360° *to* 21:1, 15% TW, natural shape partial-arc	41	53	1.70	1.89	4.04	5.18
41	c	6c	Case 6c with deep initial surface flaw	Initial Surface Flaw *from* Uniform, 10% TW 360° *to* 21:1, 40% TW, natural shape partial-arc	41	44	1.70	1.77	4.04	4.70
42	c	6c	Case 6c with low crack growth exponent	CGR Exponent *from* 1.6 *to* 1.0	41	39	1.70	1.57	4.04	2.97
43	c	6c	Case 6c with high crack growth exponent	CGR Exponent *from* 1.6 *to* 2.2	41	47	1.70	1.84	4.04	4.84
44	c	12c	Case 12c with low crack growth exponent	CGR Exponent *from* 1.6 *to* 1.0	48	37	1.86	1.69	3.54	2.64
45	c	12c	Case 12c with high crack growth exponent	CGR Exponent *from* 1.6 *to* 2.2	48	46	1.86	1.91	3.54	3.86
46	b	17b	Case 17b with low crack growth exponent	CGR Exponent *from* 1.6 *to* 1.0	35	73	1.71	1.71	69.28	73.58
47	b	17b	Case 17b with high crack growth exponent	CGR Exponent *from* 1.6 *to* 2.2	35	22	1.71	1.70	69.28	63.34
48	b	17b	Case 17b with reduced crack front pressure	Crack Front Pressure *from* 2235 psi *to* 1330 psi	35	39	1.71	1.73	69.28	70.05
49	c	6c	Case 6c without thermal loads for TW crack	Pm *from* 2.34 ksi *to* 2.46 ksi; Pb *from* 7.63 ksi *to* 0.94 ksi	41	145	1.70	2.85	4.04	8.57
50	b	17b	Case 17b without thermal loads for TW crack	Pm *from* 3.72 ksi *to* 3.71 ksi; Pb *from* 13.57 ksi *to* 0.79 ksi	35	293	1.71	4.33	69.28	191.43
51	b	19b	Case 19b without thermal loads for TW crack	Pm *from* 3.45 ksi *to* 3.36 ksi; Pb *from* 14.55 ksi *to* 0.90 ksi	*arrest*	*arrest*	*arrest*	*arrest*	*arrest*	*arrest*
52	c	1c	Case 1c with detailed nozzle-to-safe end geometry	Geometry *from* cylinder *to* detailed nozzle-to-safe end	109	94	2.24	2.26	5.81	6.61
52	d	1b	Case 1b with detailed nozzle-to-safe end geometry and direct FEA WRS interpolation	Geometry *from* cylinder *to* detailed nozzle-to-safe end; WRS *from* thermal simulation *to* direct FEA interpolation	*arrest*	*arrest*	*arrest*	*arrest*	*arrest*	*arrest*
53	b	17b	Case 17b with detailed nozzle-to-safe end geometry	Geometry *from* cylinder *to* detailed nozzle-to-safe end	35	49	1.71	1.69	69.28	42.35
S1	a	17a	Case 17a with 360° initial surface flaw	Initial Surface Flaw *from* 21:1, 26% TW, natural shape partial-arc *to* Uniform, 10% TW 360°	*arrest*	*arrest*	*arrest*	*arrest*	*arrest*	*arrest*
S1	b	17b	Case 17b with 360° initial surface flaw	Initial Surface Flaw *from* 21:1, 26% TW, natural shape partial-arc *to* Uniform, 10% TW 360°	35	*not applicable*	1.71	1.03	69.28	*not applicable*
S2	b	17b	Case 17b with 360° initial surface flaw and low bending moment	Initial Surface Flaw *from* 21:1, 26% TW, natural shape partial-arc *to* Uniform, 10% TW 360°; Pb *from* 13.57 ksi *to* 8.40 ksi	35	4	1.71	1.28	69.28	6.00
S3	b	17b	Case 17b with short crack length initial surface flaw	Initial Surface Flaw *from* 21:1, 26% TW, natural shape partial-arc *to* 5.6:1, 10% TW, natural shape partial-arc	35	74	1.71	2.03	69.28	87.49
S4	b	17b	Case 17b with additional crack flaw at position 1	after 7 days of leakage w/ additional 21:1 partial-arc crack at position 1 (Fig. 7-14)	35	*not applicable*	1.65 (note 2)	1.43 (note 2)	69.28	*not applicable*
S5	b	17b	Case 17b with additional crack flaw at position 2	after 7 days of leakage w/ additional 21:1 partial-arc crack at position 2 (Fig. 7-14)	35	*not applicable*	1.65 (note 2)	1.48 (note 2)	69.28	*not applicable*
S6	b	17b	Case 17b with additional crack flaw at position 3	after 7 days of leakage w/ additional 21:1 partial-arc crack at position 3 (Fig. 7-14)	35	*not applicable*	1.65 (note 2)	1.29 (note 2)	69.28	*not applicable*
S7	b	17b	Case 17b with additional limiting crack	after 7 days of leakage w/ additional limiting partial-arc crack at 95% TW (Fig. 7-14)	35	*not applicable*	1.65 (note 2)	1.44 (note 2)	69.28	*not applicable*
S8	b	19b	Case 19b with 360° initial surface flaw	Initial Surface Flaw *from* 21:1, 26% TW, natural shape partial-arc *to* Uniform, 10% TW 360°	*arrest*	*arrest*	*arrest*	*arrest*	*arrest*	*arrest*
S9	b	17b	Case 17b with additional crack flaw at bottom of weld	Number of Initial Flaws *from* single 21:1 partial-arc crack at top of weld *to* 21:1 partial-arc cracks at top and bottom of weld (Fig. 7-15)	35	29	1.71	1.60	69.28	69.28

Note 2: Stability Margin Factor after 7 days of leakage

Matrix Results
Multiple Crack Cases



Profiles of Pairs of Additional Cracks Applied in Stability Calculations for Cases S4b through S7b Based on Case 17b



Case S9b Growth Progression Based on Individual Growth of Initial 21:1 Aspect Ratio 26% through-wall Flaws Placed at Top and Bottom of Weld Cross Section

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Sensitivity Case Matrix
Matrix Conclusions

- All 109 completed cases in the main sensitivity matrix showed either
  - stable crack arrest (60 cases), or
  - crack leakage and crack stability results satisfying the evaluation criteria (49 cases)
  - generally considerable margins beyond evaluation criteria
- 10 supplemental cases further investigated the effect of multiple flaws on limiting surge nozzle cases
  - Conservative application of the three Wolf Creek surge nozzle indications with limiting surge nozzles (fill-in weld and relatively high moment load) gives results meeting the evaluation criteria with additional margin
  - A case with two long initial partial-arc flaws covering 46% of the ID circumference as opposed to a single initial flaw covering half this circumferential extent (and centered at the location of maximum axial bending stress) has only a modest effect on crack stability
  - On this basis, it is concluded that the concern for multiple flaws in the limiting surge nozzles is adequately addressed by cases that satisfy the evaluation criteria with additional margin

Conclusions

- Assumption of semi-elliptical flaw shape shown to result in large unnecessary overconservatism
- All 51 subject welds are adequately covered by crack growth sensitivity cases that satisfy the evaluation criteria
  - All 109 cases in the main sensitivity matrix satisfied the evaluation criteria, with most cases showing large margins in leakage time and in crack stability
  - The margins in the matrix results demonstrated that even cases representing an unlikely combination of detrimental factors are likely to result in sufficient time for leak detection prior to rupture
  - The matrix results also showed sufficient margin to address modeling uncertainties such as those associated with the potential for multiple through-wall crack segments
  - A set of supplementary cases satisfactorily addressed the concern for multiple flaws in each of the limiting surge nozzles

Conclusions (cont'd)

- Results show tendency of circumferential surface cracks to show stable arrest
  - Axisymmetric welding residual stress profile must self-balance
  - Consistent with Wolf Creek experience given unlikeliness that four indications found in narrow depth band were growing rapidly at that time
- Sensitivity cases indicate a large beneficial effect of relaxation of secondary loads upon through-wall penetration
  - Detailed evaluations tend to support such a relaxation effect
  - Not fully credited in main cases
- In summary, this study demonstrates the viability of leak detection to preclude the potential for rupture for the pressurizer nozzle DM welds in the group of subject PWRs