

Advanced FEA Crack Growth Calculations for Evaluation of PWR Pressurizer Nozzle Dissimilar Metal Weld Circumferential PWSCC

Sponsored by: EPRI Materials Reliability Program

Presented To:

Expert Review Panel for Advanced FEA Crack Growth Calculations

Presented By:

Glenn White

John Broussard

Jean Collin

Dominion Engineering, Inc.

Thursday, May 31 and Friday, June 1, 2007

Meeting on Implications of Wolf Creek Dissimilar Metal Weld Inspections

DEI Offices

Reston, Virginia



11730 Plaza America Dr. #310
Reston, VA 20190
703.437.1155
www.domeng.com

Thursday Morning Agenda

- Introductions – Industry and NRC
- Status of Industry Work (Industry)
 - Update on Weld Fabrication/Repair Information
 - WRS Modeling
 - EPFM vs. Limit Load Issue Update
 - Primary and Secondary Stress Inclusion Issue Update
 - K Validation
 - Model Convergence
 - Update on Timeline of Activities
 - WRS Modeling
 - Validation Studies
 - Leak-Rate Studies
- Status of NRC Confirmatory Research (NRC)
 - K Validation
 - Model Convergence
 - Update on Timeline of Activities
 - WRS
 - Phase II Sensitivity Studies
 - Validation Studies
 - Leak-Rate Studies

Thursday Afternoon Agenda

- Presentation & Discussion of Proposed Sensitivity Matrix (Industry)
 - List of Sensitivity Matrix Cases that Industry will Evaluate
 - Loads/Geometries/WRS/CGR/Multiple Crack Growth

Friday Agenda

- Discussion of Proposed Sensitivity Matrix (Industry & NRC)
- Proposed Acceptance Criteria and Safety Factors (Industry)
- Plans for next meeting(s) (Industry & NRC)
- Meeting Summary and Conclusions (Industry & NRC)

Thursday Morning Agenda

- Introductions – Industry and NRC
- Status of Industry Work (Industry)
- Status of NRC Confirmatory Research (NRC)

Principal Meeting Participants

- EPRI Project Management / Support
 - Craig Harrington, EPRI
 - Tim Gilman, Structural Integrity Associates
- Project Team
 - Glenn White, DEI
 - John Broussard, DEI
 - Jean Collin, DEI
- Expert Review Panel
 - Ted Anderson, Quest Reliability, LLC (via phone)
 - Warren Bamford, Westinghouse
 - Doug Killian, AREVA
 - Cameron Martin, Westinghouse
 - Pete Riccardella, Structural Integrity Associates
- NRC Participants
 - Al Csontos, NRC Research
 - Mauricio Gutierrez, NRC NRR
 - Tim Lupold, NRC NRR
 - Dave Rudland, EMC2
 - Simon Sheng, NRC NRR
 - Ted Sullivan, NRC NRR

Status of Industry Work

Topics

- Update on Weld Fabrication/Repair Information
- WRS Modeling
- EPFM vs. Limit Load Issue Update
- Primary and Secondary Stress Inclusion Issue Update
- K Validation
- Model Convergence
- Update on Timeline of Activities
 - WRS Modeling
 - Validation Studies
 - Leak-Rate Studies

Update on Weld Fab/Repair Information

Summary

- A summary of the previously compiled weld repair information is shown on the next two slides
- Warren Bamford and Cameron Martin of Westinghouse to present the update
 - Weld fabrication
 - Weld repair

Weld Fab/Repair Information

PRELIMINARY Weld Repair Summary Table

Table Line	Plant Code	Nozzle Type	Nozzle Count	Design #	Buttering or Weld	ID/OD (% circ.)	Alloy 82 or 182	PWHT after Repair?	# Defect or Repair Areas	Defect/Repair Area #1		Defect/Repair Area #2		Defect/Repair Area #3		Defect/Repair Area #4		Defect/Repair Area #5		Defect/Repair Area #6	
										Length (in.)	Depth (in.)	Length (in.)	Depth (in.)	Length (in.)	Depth (in.)	Length (in.)	Depth (in.)	Length (in.)	Depth (in.)	Length (in.)	Depth (in.)
1	A	Safety A	1	1a	weld	OD	N/A	N/A	4	N/A	~1/2	N/A	~1/2	N/A	~1/2	N/A	~1/2				
2	A	Safety B	2	1a	weld	ID	N/A	N/A	1	1/2	5/8										
3	E	Relief	3	1a	weld	OD	N/A	N	N/A	N/A	N/A										
4	E	Safety C	4	1a	weld	ID<22%	N/A	N	N/A	N/A	N/A										
5	H	Safety A	5	1a	weld	ID	82	Y	N/A	N/A	N/A										
6						OD	82	Y	N/A	N/A	N/A										
7	F	Safety A	6	1b	NR	NR	NR	NR	NR	NR	NR										
8	B	Relief	7	2a	weld	OD	182	N/A	1	0.5	0.375										
9	C	Safety A	8	2b	NR	NR	NR	NR	NR	NR	NR										
10	C	Safety B	9	2b	NR	NR	NR	NR	NR	NR	NR										
11	C	Safety C	10	2b	NR	NR	NR	NR	NR	NR	NR										
12	D	Safety A	11	3	butter	N/A	N/A	Y	N/A	N/A	N/A										
13	E	Spray	12	4	butter	ID	82	Y	N/A	N/A	~0.3										
14					weld	OD	N/A	N	N/A	N/A	N/A										
15	C	Spray	13	5	NR	NR	NR	NR	NR	NR	NR										
16	A	Surge	14	8	weld	ID	N/A	N/A	5	1.5	5/16	3.75	0.5	2	3/16	2.5	5/16	2	5/16		
17						OD	N/A	N/A	3	2.5	0.5	2	0.5	1	3/16						
18	E	Surge	15	8	weld	ID<10%	82	N	3	N/A	N/A	N/A	N/A	N/A	N/A						
19	B	Surge	16	8	butter	N/A	82	Y	1	N/A	N/A										
20					weld	OD	182	N/A	2	1.75	0.875	1.5	1								
21						ID	182	N/A	1	1.0	0.625										
22						ID	182	N/A	1	4	0.75										

Notes:

1. For Designs #2a, #2b, and #5, liner directly covers DM weld.
2. For Design #4, liner does not extend to most of DM weld.
3. For Designs #4, #5, and #6, sleeve covers but does not contact DM weld.
4. For Design #8, sleeve directly covers DM weld.
5. NR = Information not yet reported (or may not be available)
6. N/A = Information not available
7. Weld repair entries for Plants C and F are preliminary.

Weld Fab/Repair Information

PRELIMINARY Weld Repair Summary Table (cont'd)

Table Line	Plant Code	Nozzle Type	Nozzle Count	Design #	Buttering or Weld	ID/OD (% circ.)	Alloy 82 or 182	PWHT after Repair?	# Defect or Repair Areas	Defect/Repair Area #1		Defect/Repair Area #2		Defect/Repair Area #3		Defect/Repair Area #4		Defect/Repair Area #5		Defect/Repair Area #6	
										Length (in.)	Depth (in.)	Length (in.)	Depth (in.)	Length (in.)	Depth (in.)	Length (in.)	Depth (in.)	Length (in.)	Depth (in.)	Length (in.)	Depth (in.)
WC1	J	Relief	WC1	1a	butter	N/A	82/182	Y	N/A	N/A	N/A										
WC2						ID+OD	82	Y	2	1/2	7/16ID	1	7/16OD								
WC3						OD	182	Y	1	1	3/4										
WC4						ID	82	Y	3	3/4	3/4	2-1/4	3/4	1/2	3/4						
WC5						OD	182	Y	3	1	3/4	2-1/4	3/4	1/2	3/4						
WC6					weld	OD	82	N/A	1	1-1/4	1/2										
WC7						ID	82	N/A	1	1/2	1/2										
WC8	J	Safety A	WC2	1a	butter	N/A	182	Y	N/A	N/A	1/8										
WC9					weld	ID	82	N/A	2	1-1/4	11/32	7/8	11/32								
WC10	J	Safety B	WC3	1a	weld	ID	82	N/A	6	2-1/2	3/4	1	1/2	1-1/2	1/2	1	1/2	2-1/2	3/4	2-1/2	3/4
WC11							82	N/A	6	1-1/2	1/2	1-1/4	1	3/4	7/8	1-1/2	3/8	1	1-1/16	1/2	1/2
WC12	J	Spray	WC4	4	butter	lip/bondline	82	Y	N/A	N/A	N/A										
WC13	J	Surge	WC5	8	butter	OD	182	Y	2	7/8	9/16	1-1/8	1								
WC14					weld	ID	82	Y	1	1	7/16										

Notes:

1. For Designs #2a, #2b, and #5, liner directly covers DM weld.
2. For Design #4, liner does not extend to most of DM weld.
3. For Designs #4, #5, and #6, sleeve covers but does not contact DM weld.
4. For Design #8, sleeve directly covers DM weld.
5. NR = Information not yet reported (or may not be available)
6. N/A = Information not available
7. Weld repair entries for Plants C and F are preliminary.

WRS Modeling

Introduction

- DEI is currently running the WRS cases discussed at the May 1 and May 8 meetings
 - See slides that follow
- We also have examined the MRP-106 WRS results in greater detail:
 - Generic MRP-106 surge nozzle case
 - Generic MRP-106 safety and relief nozzle case
 - New figures to be presented separate from this presentation package

Welding Residual Stress (WRS) Analysis

Case Matrix

- May 1 and May 8 meetings identified key geometry cases for consideration
- Surge Nozzle
 - No repairs with fill-in weld
 - 0.5" (or 5/16") repair followed by fill-in weld
 - CE nozzle case with no fill-in weld
- Safety/Relief Nozzle
 - No repairs with safe end ID weld buildup
 - No repairs with liner fillet weld
 - 3/4" deep ID repair followed by liner fillet weld
- Spray Nozzle
 - Cases deferred until further information available

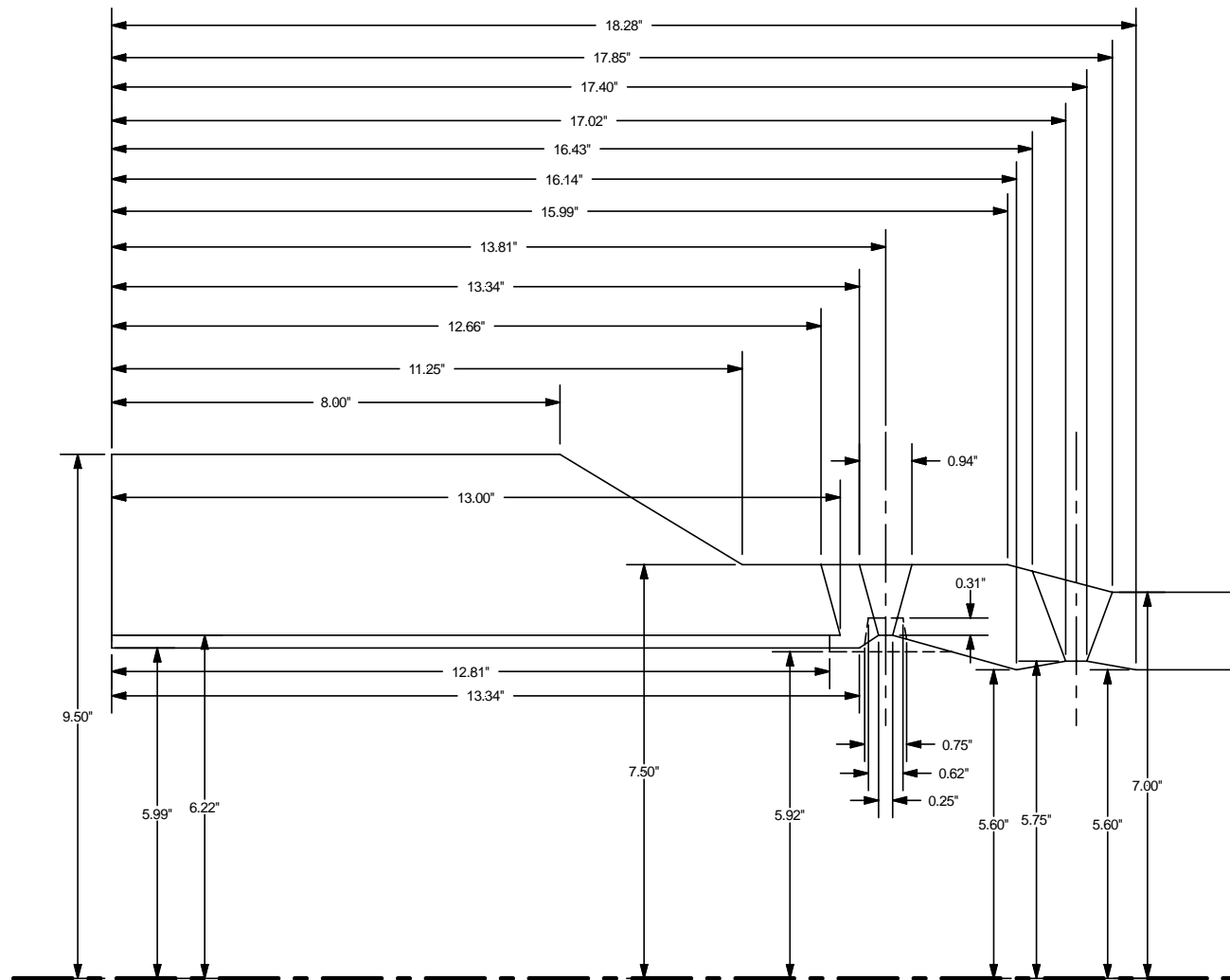
WRS Analysis

Analysis Cases Completed

- Surge Nozzle
 - Type 8 (Westinghouse) base case, includes fill-in weld
 - Type 8 with 5/16" ID repair (fill-in weld follows repair)
- Safety/Relief Nozzle
 - Type 1a (clad, no liner) base case
 - Type 2b (liner with fillet weld) base case
 - Type 1a with safe end ID weld buildup
- All cases analyzed with safe end to pipe butt weld
 - Initial cases indicated noticeable effect of butt weld, therefore included in all cases for completeness

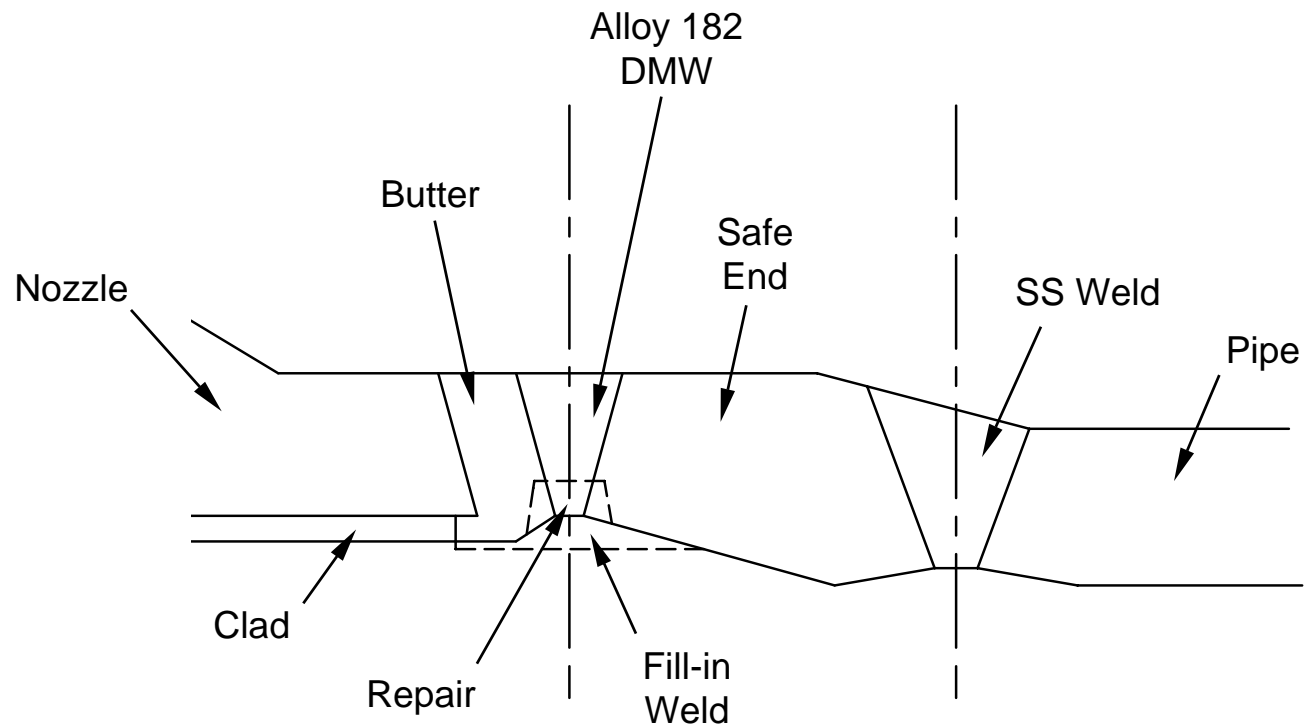
WRS Analysis

Type 8 Surge Nozzle – Model Dimensions



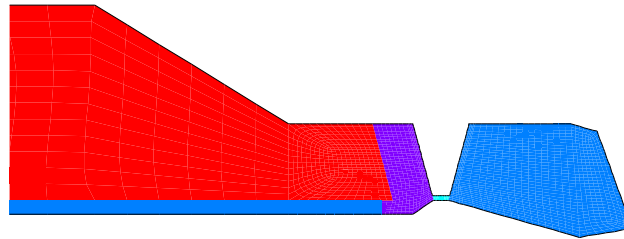
WRS Analysis

Type 8 Surge Nozzle – Weld Region Detail

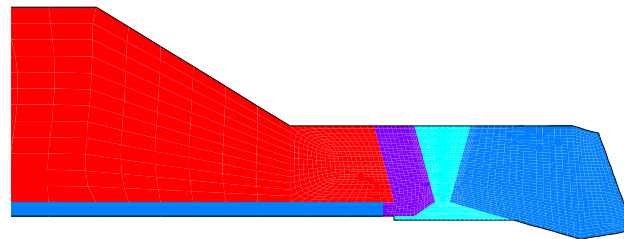


WRS Analysis

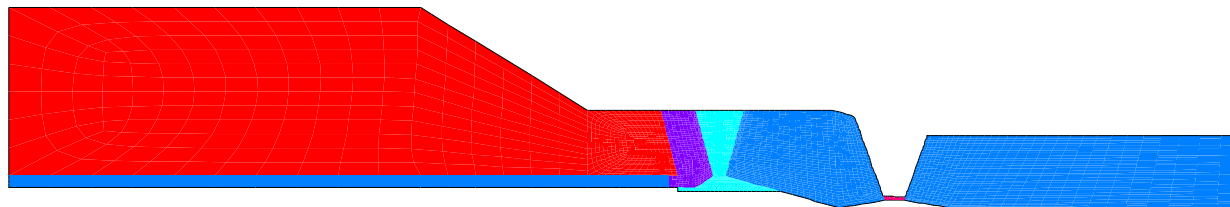
Type 8 Surge Nozzle (Base Case)



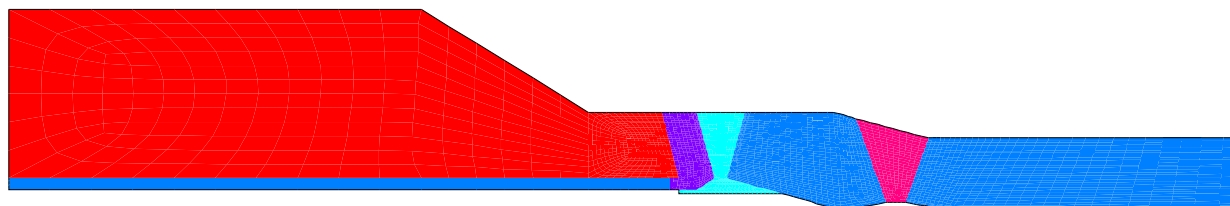
Starting Model



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



Begin SS Weld (8 layers)

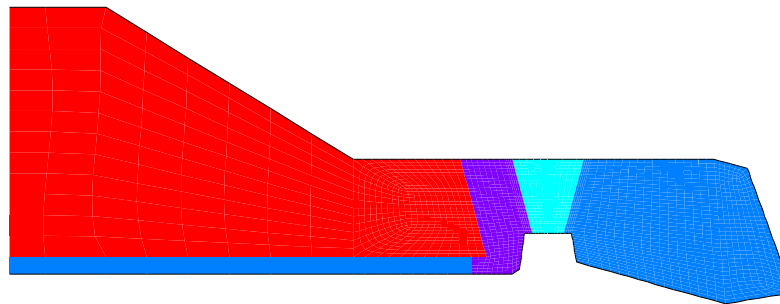


Model Complete

WRS Analysis

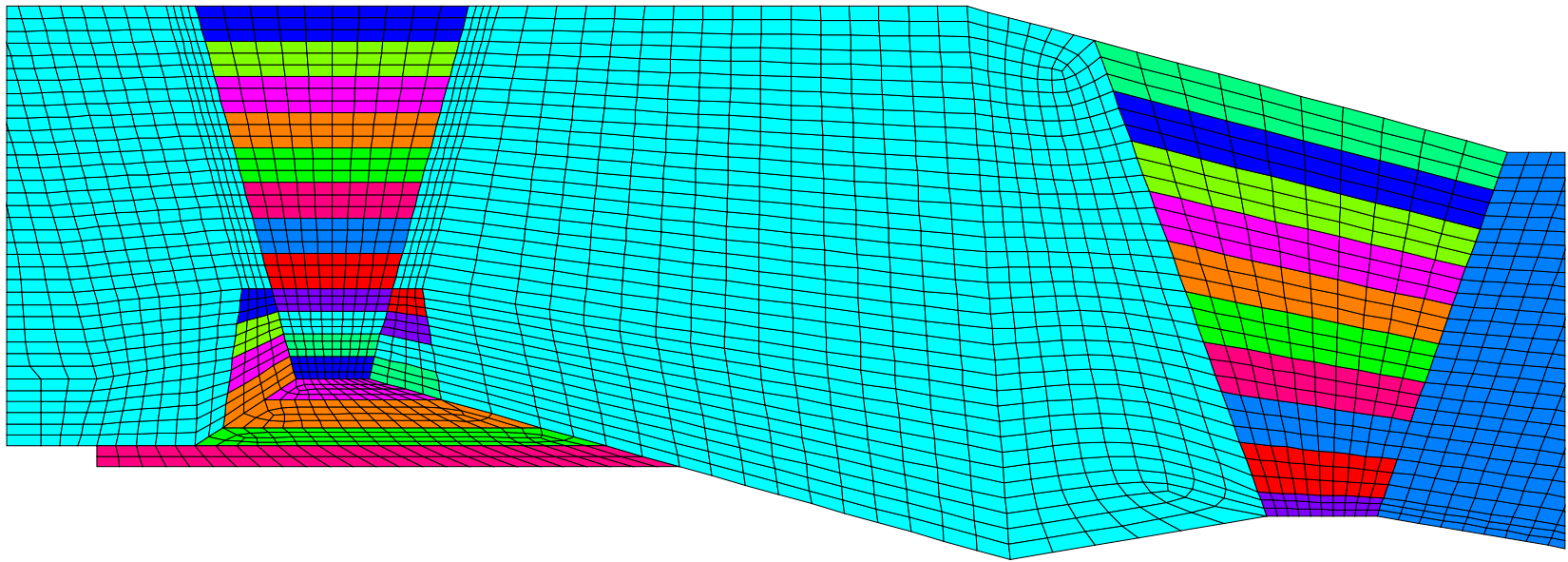
Type 8 Surge Nozzle Weld Sequence

- DMW: 11 layers built on initial land of material
- DMW: Initial land removed then welded as 12th pass
- Fill-in Weld: 4 layers built out
- Safe end to pipe: 7 layers built on initial land of material
 - Initial land not removed and welded
- ID repair performed in 4 layers prior to Fill-in Weld step



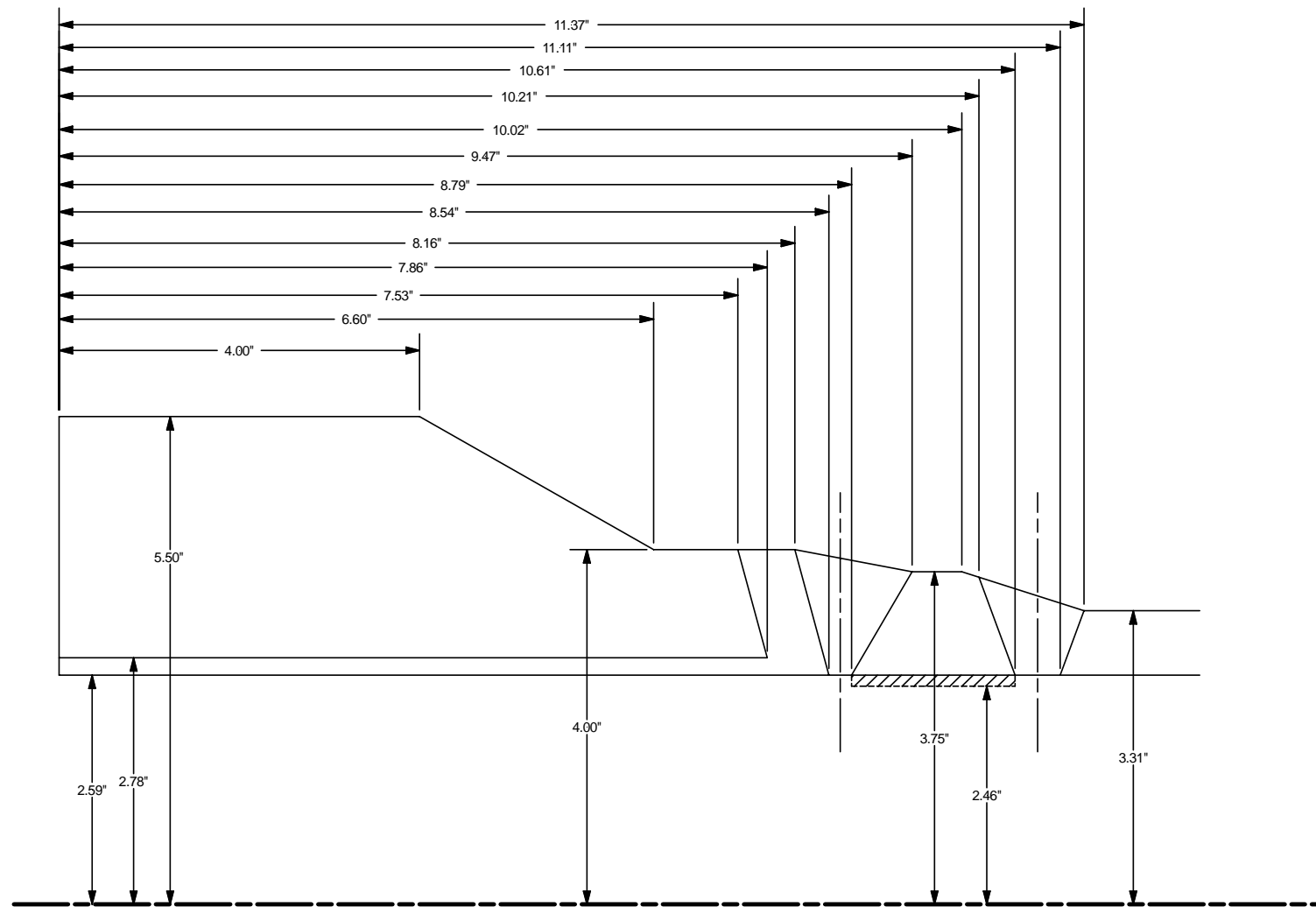
WRS Analysis

Type 8 Surge Nozzle Model – Element Mesh and Weld Layers



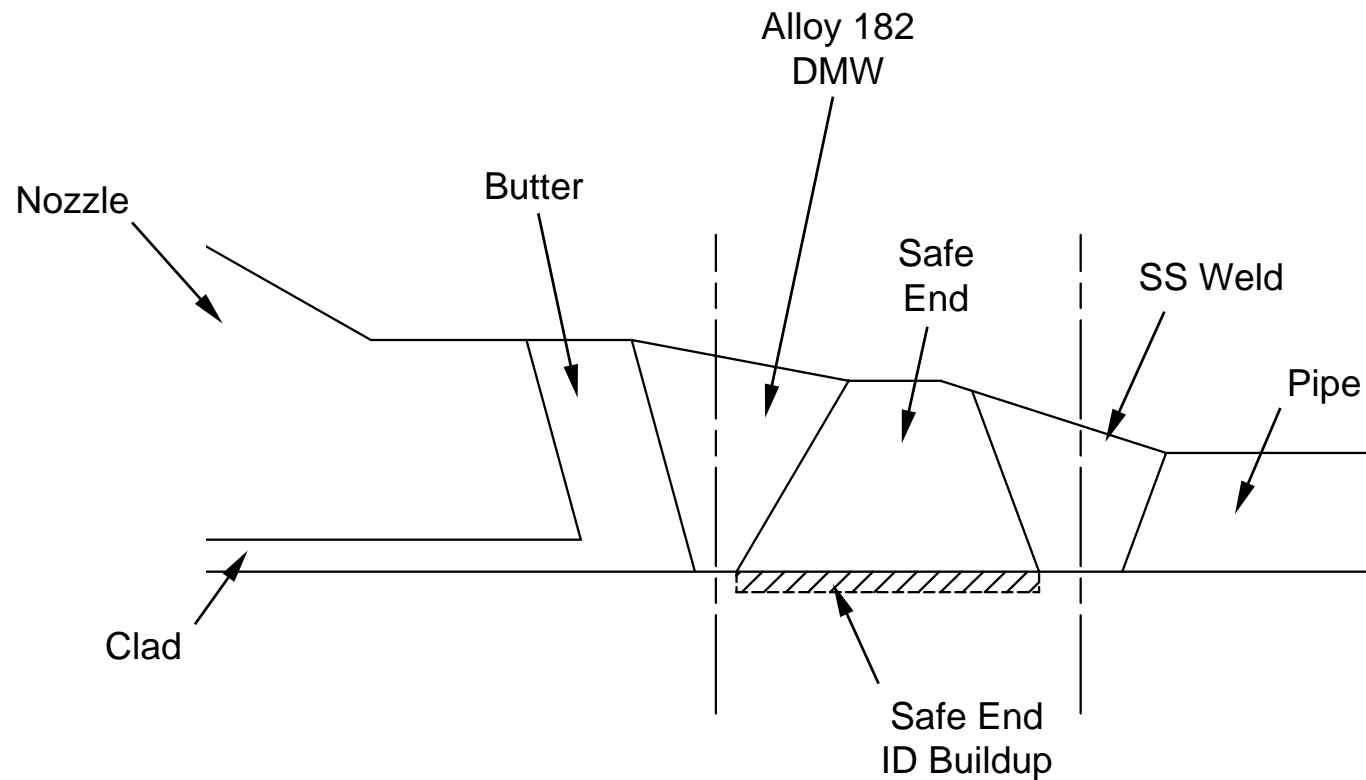
WRS Analysis

Type 1a Safety/Relief Nozzle – Model Dimensions



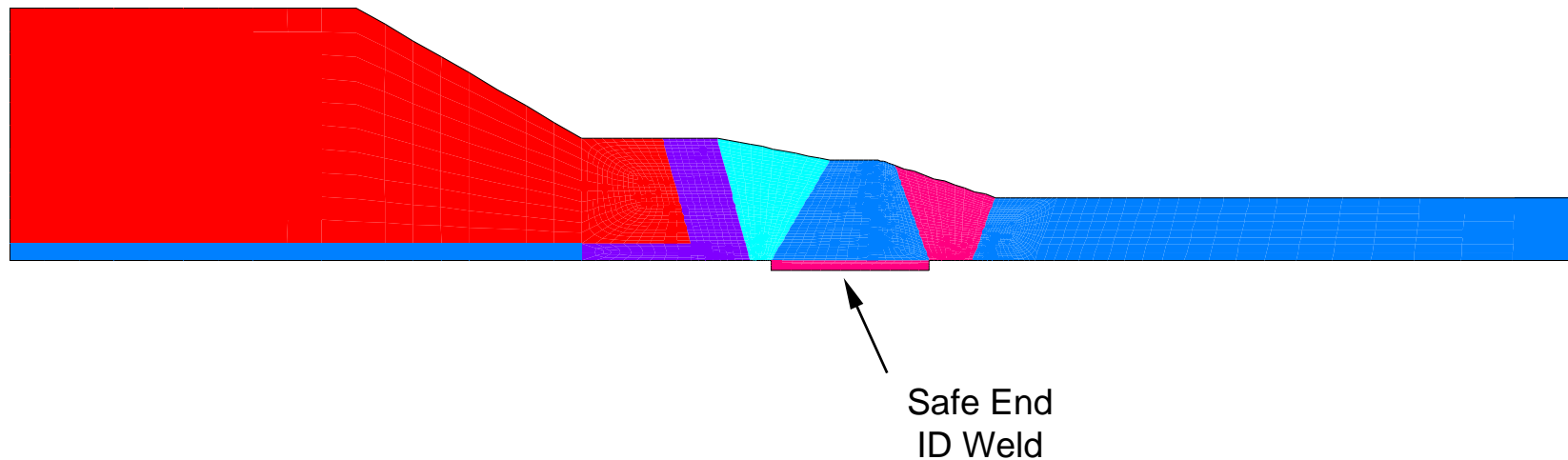
WRS Analysis

Type 1a Safety/Relief Nozzle – Weld Region Detail



WRS Analysis

Type 1a Safety/Relief Nozzle Model



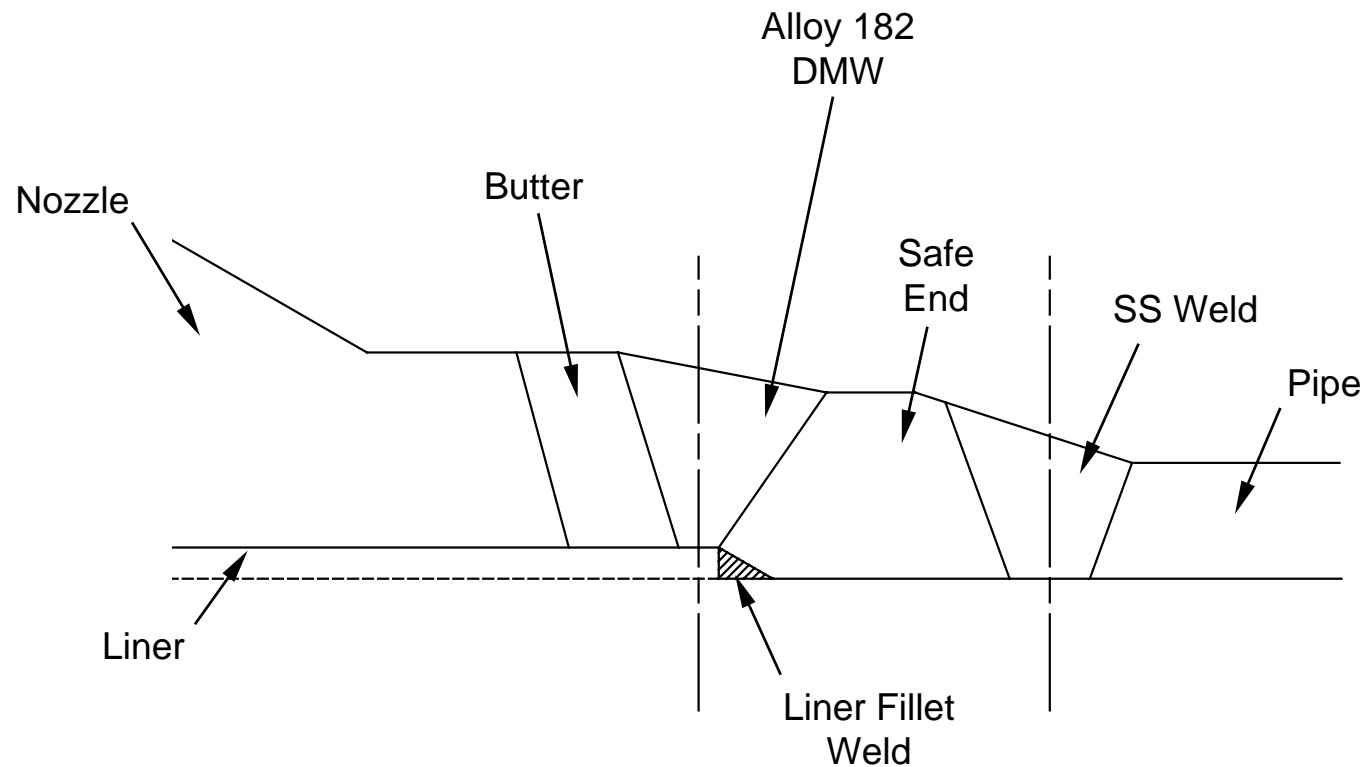
WRS Analysis

Type 1a Safety/Relief Nozzle Weld Sequence

- DMW: 11 layers built on initial land of material
- DMW: Initial land removed then welded as 12th pass
- Safe end to pipe: 9 layers built on initial land of material
 - Initial land not removed and welded
- Safe end ID weld buildup performed in 2 layers prior to safe end to pipe weld step

WRS Analysis

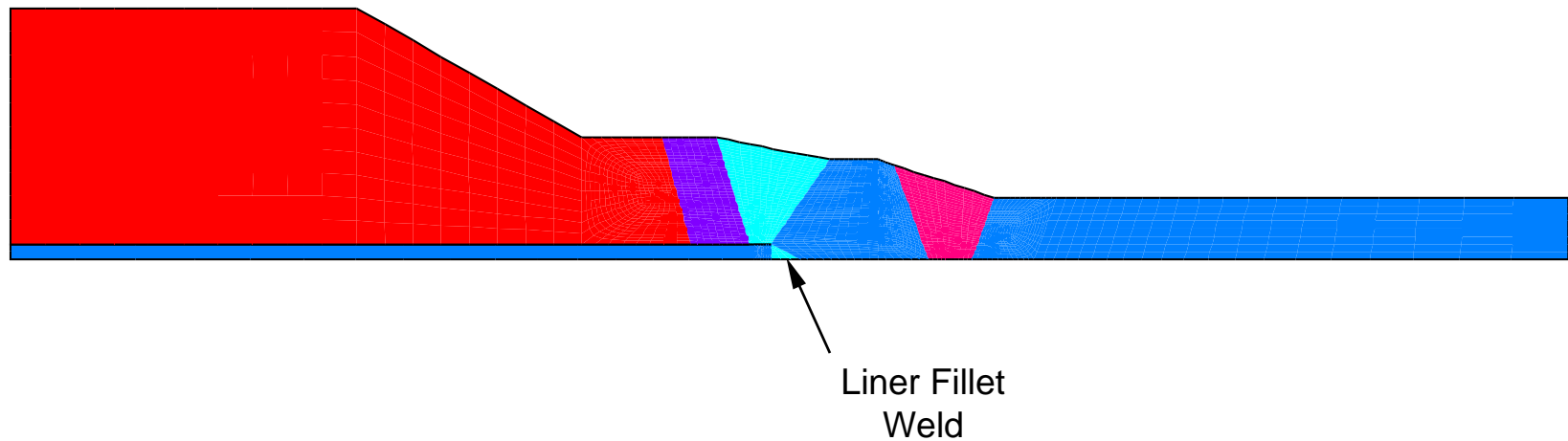
Type 2b Safety/Relief Nozzle – Weld Region Detail



Liner Fillet Weld performed after DMW complete, prior to SS weld

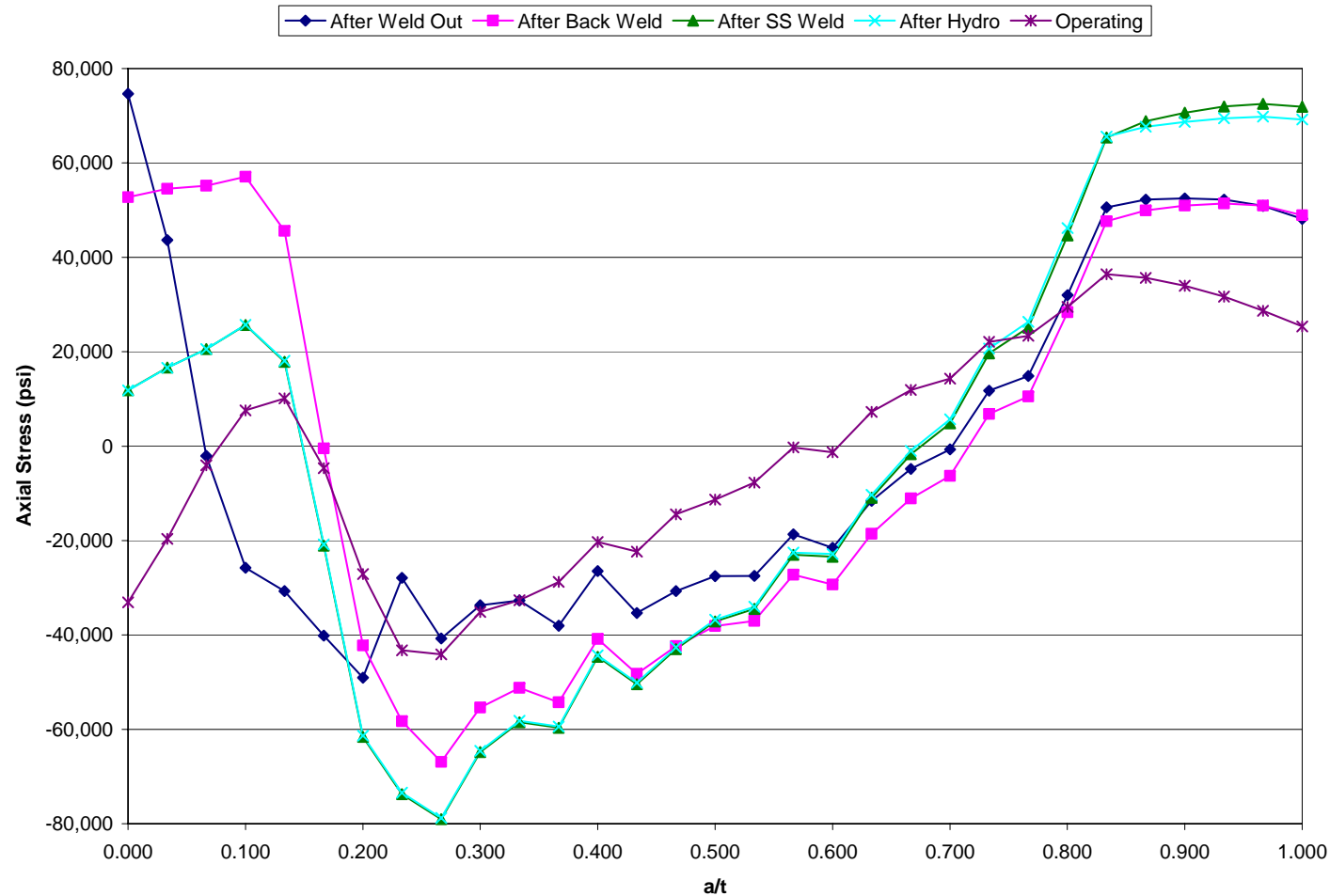
WRS Analysis

Type 2b Safety/Relief Nozzle Model



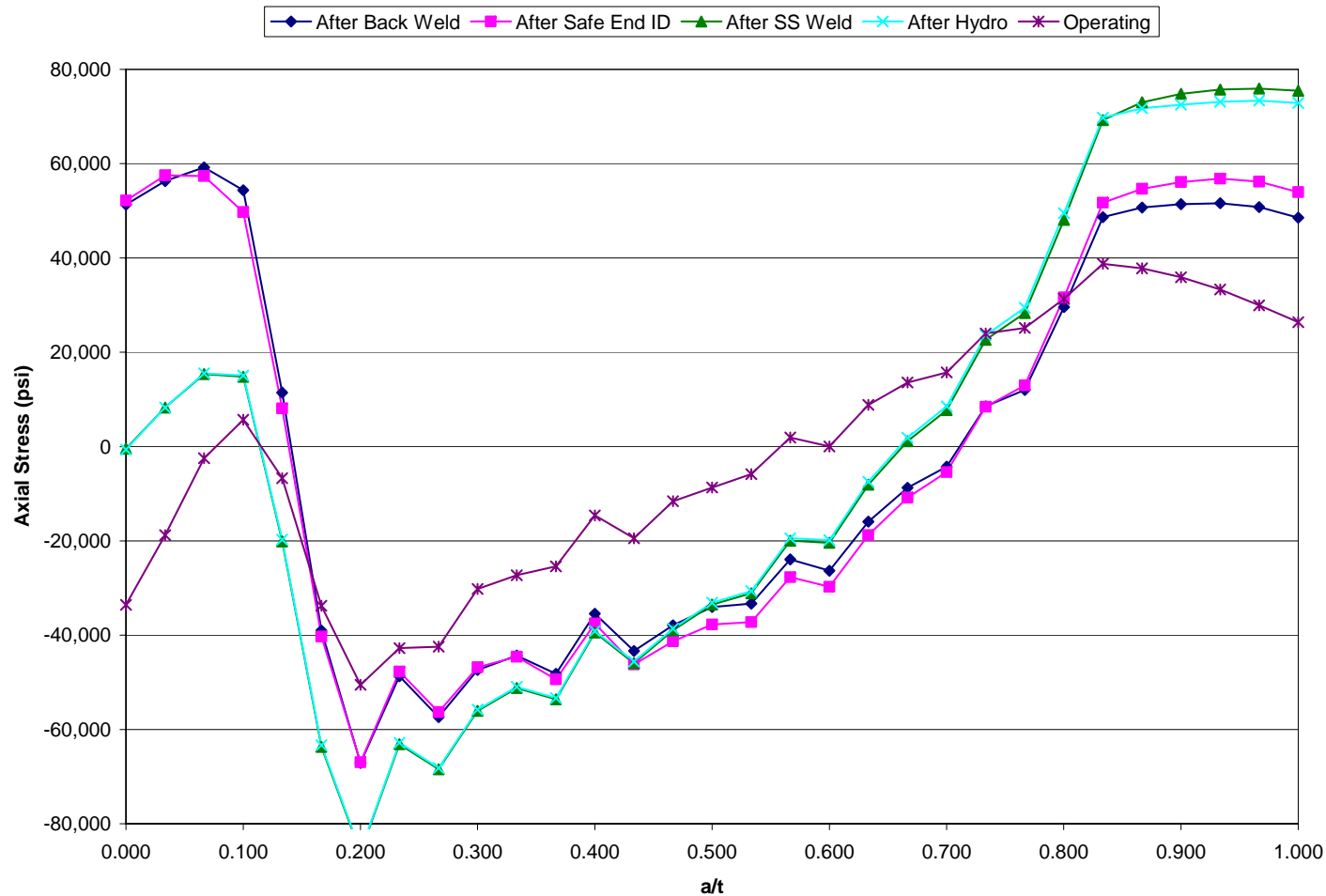
WRS Analysis

Type 1a Safety/Relief Results – Base Case – Axial Stresses Weld C/L



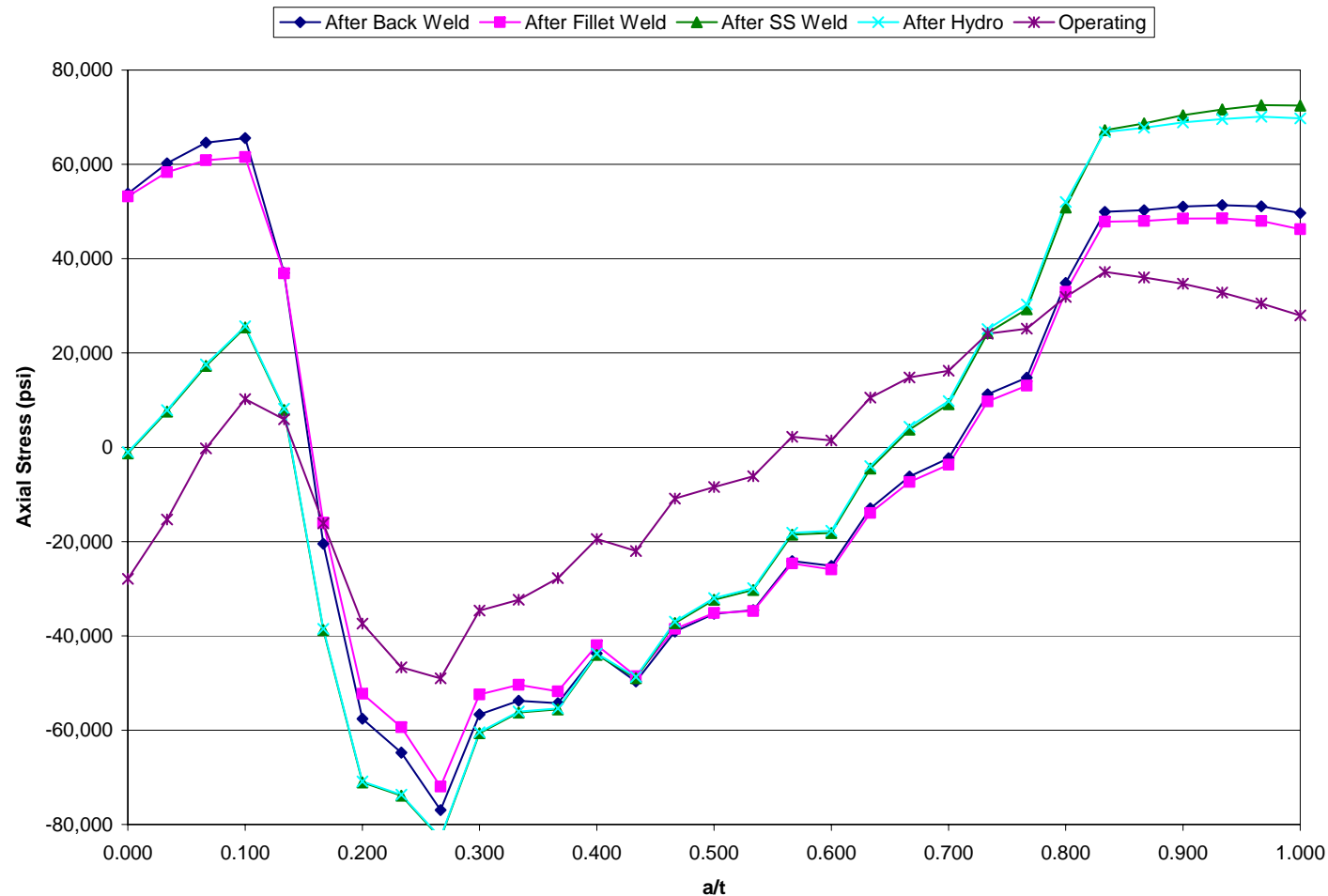
WRS Analysis

Type 1a S/R Results – Safe End ID Weld – Axial Stresses Weld C/L



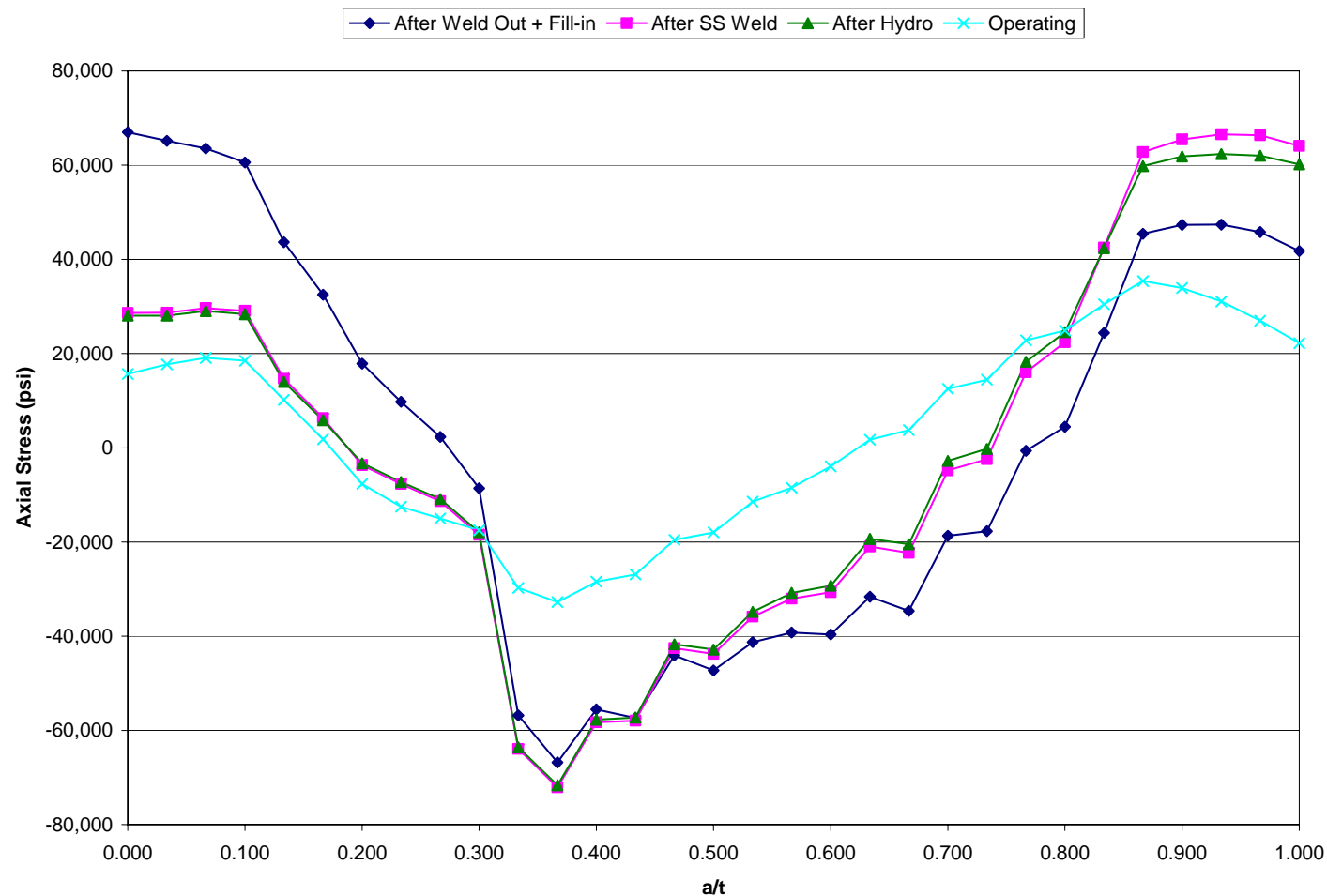
WRS Analysis

Type 2b Safety/Relief Results – Base Case – Axial Stresses Weld C/L



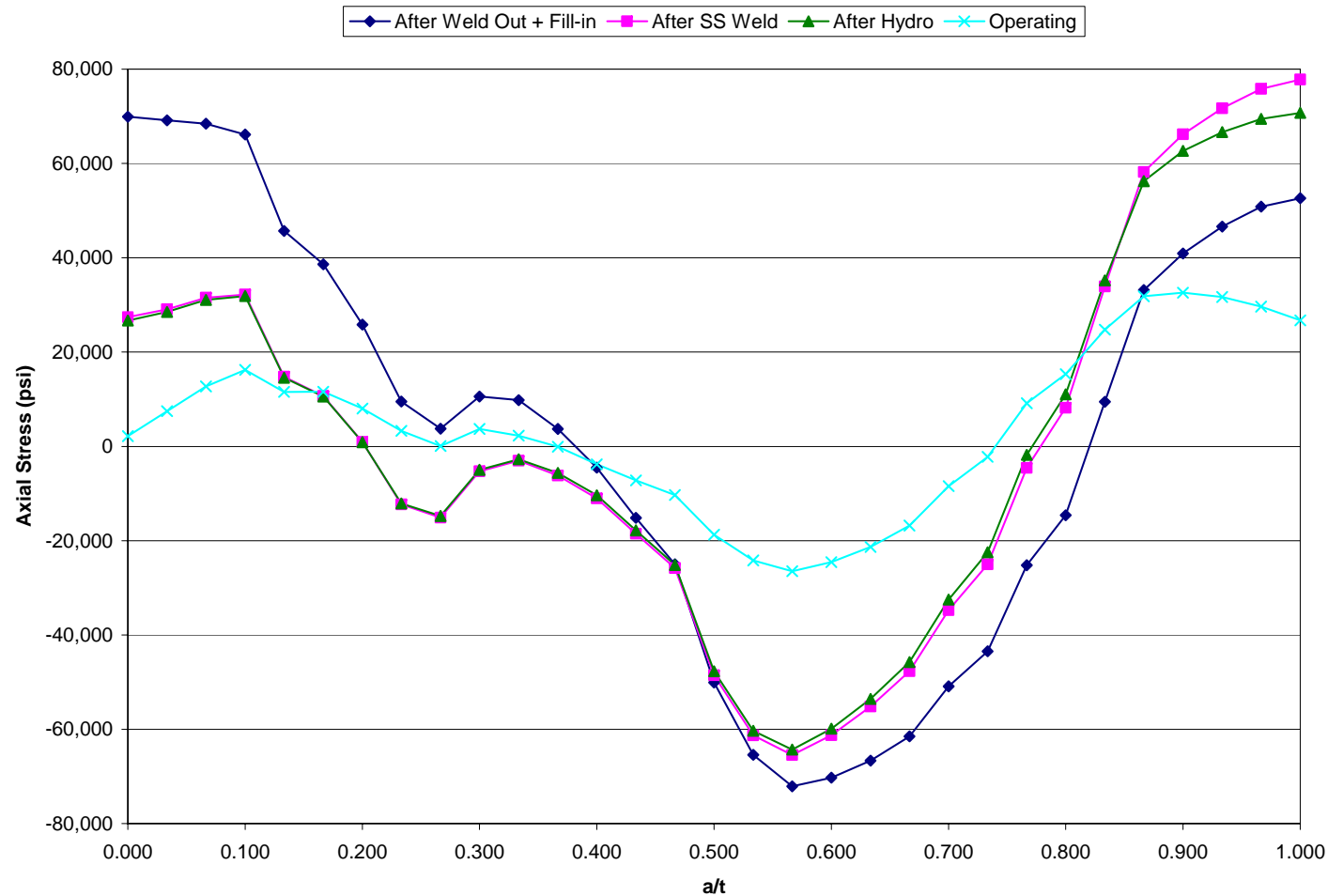
WRS Analysis

Type 8 Surge Nozzle Results – Base Case – Axial Stresses Weld C/L



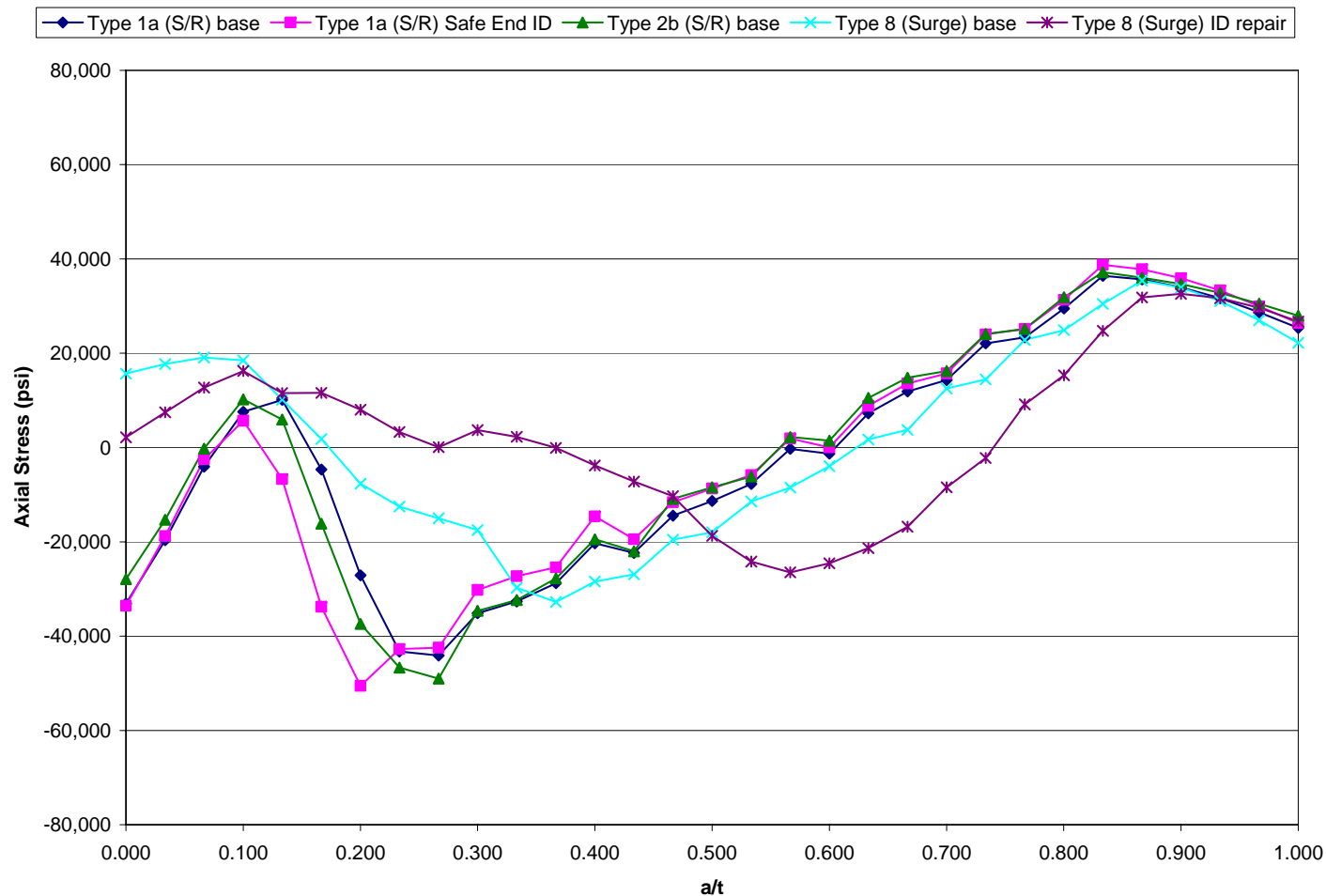
WRS Analysis

Type 8 Surge Nozzle Results – ID Repair – Axial Stresses Weld C/L



WRS Analysis

Overall Operating Condition Summary – Axial Stresses Weld C/L



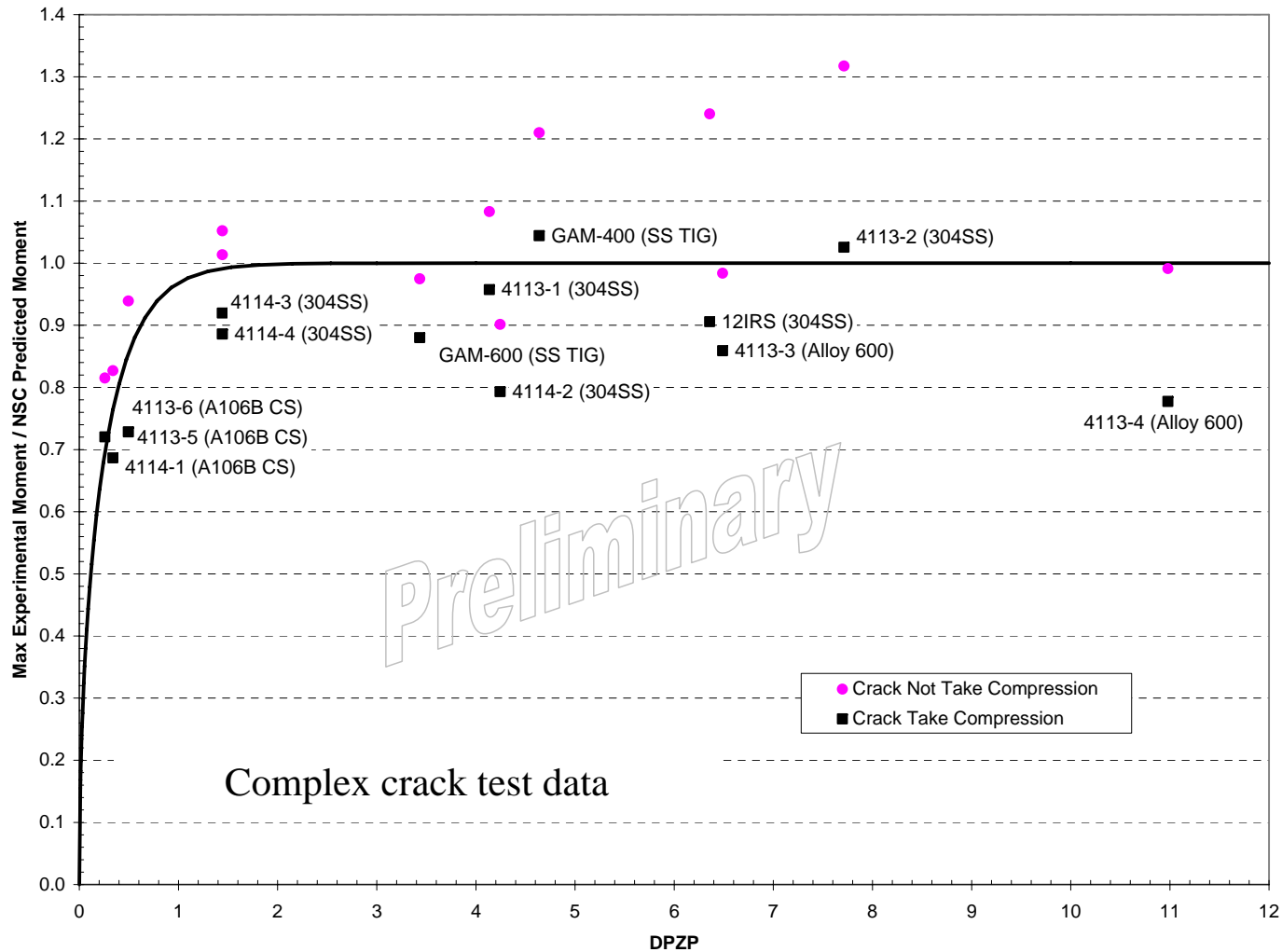
EPFM vs. Limit Load Issue Update

Summary

- Experimental data for failure of complex cracks in pipes have been evaluated to investigate limit load prediction vs. maximum experimental load
- DPZP proposed for complex cracks has been used to plot the results of the comparison
- Approach covered in May 8 presentation by Pete Riccardella of Structural Integrity Associates
- Work to evaluate apparent toughness data for complex crack tests using enhanced reference stress (ERS) approach by Kim still in progress
 - Challenge is to calculate elastic J-integral for test complex crack geometry

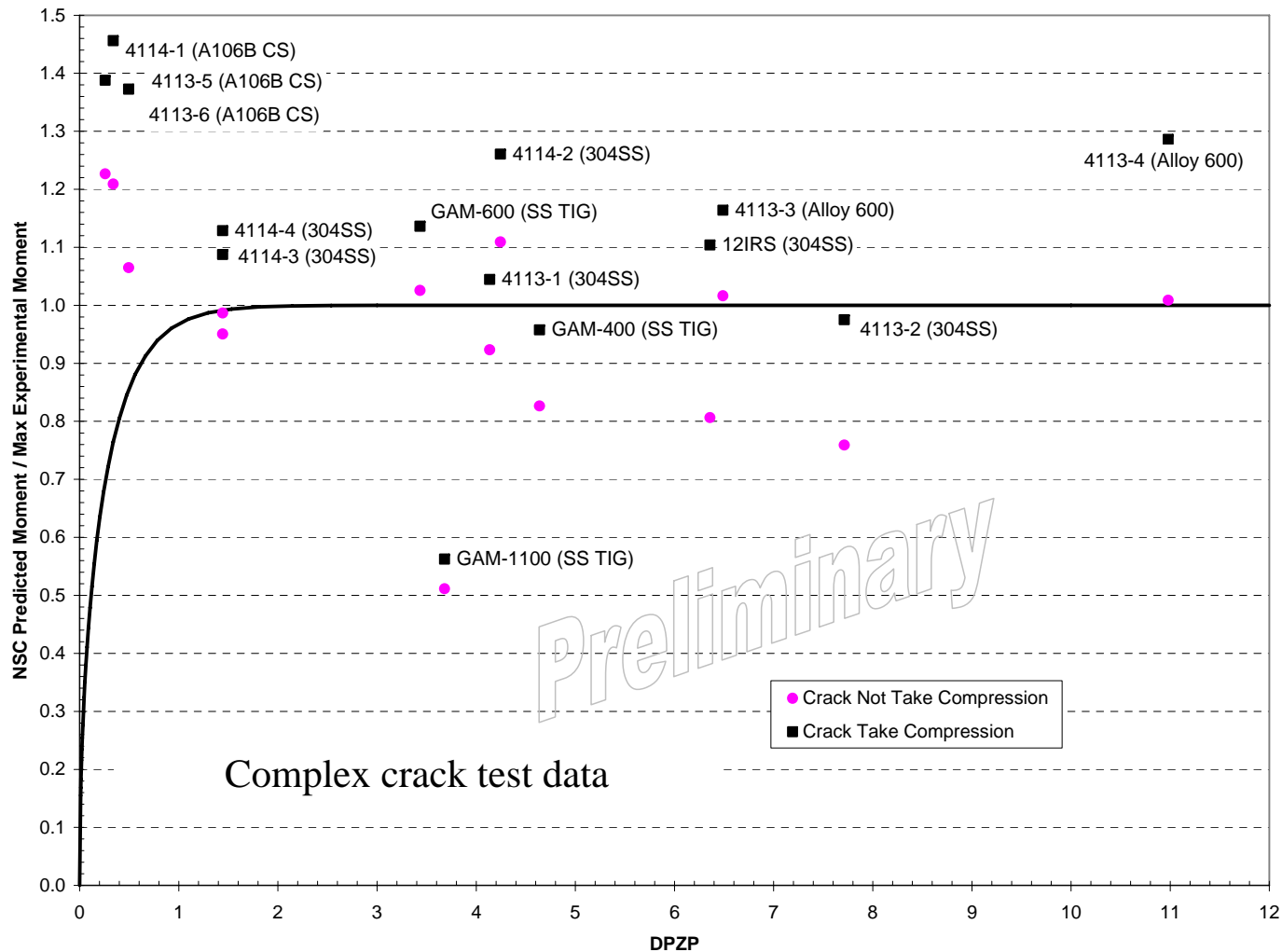
EPFM vs. Limit Load Issue Update

Max Experimental Moment Divided by NSC Predicted Moment



EPFM vs. Limit Load Issue Update

NSC Predicted Moment Divided by Max Experimental Moment



Secondary Stress Inclusion Issue Update

Introduction

- See presentations on this topic by
 - Ted Anderson of Quest Reliability, LLC on elastic-plastic FEA calculations of response of pipe with through-wall crack to fixed end rotation
 - Pete Riccardella of Structural Integrity Associates on surge line rotation study

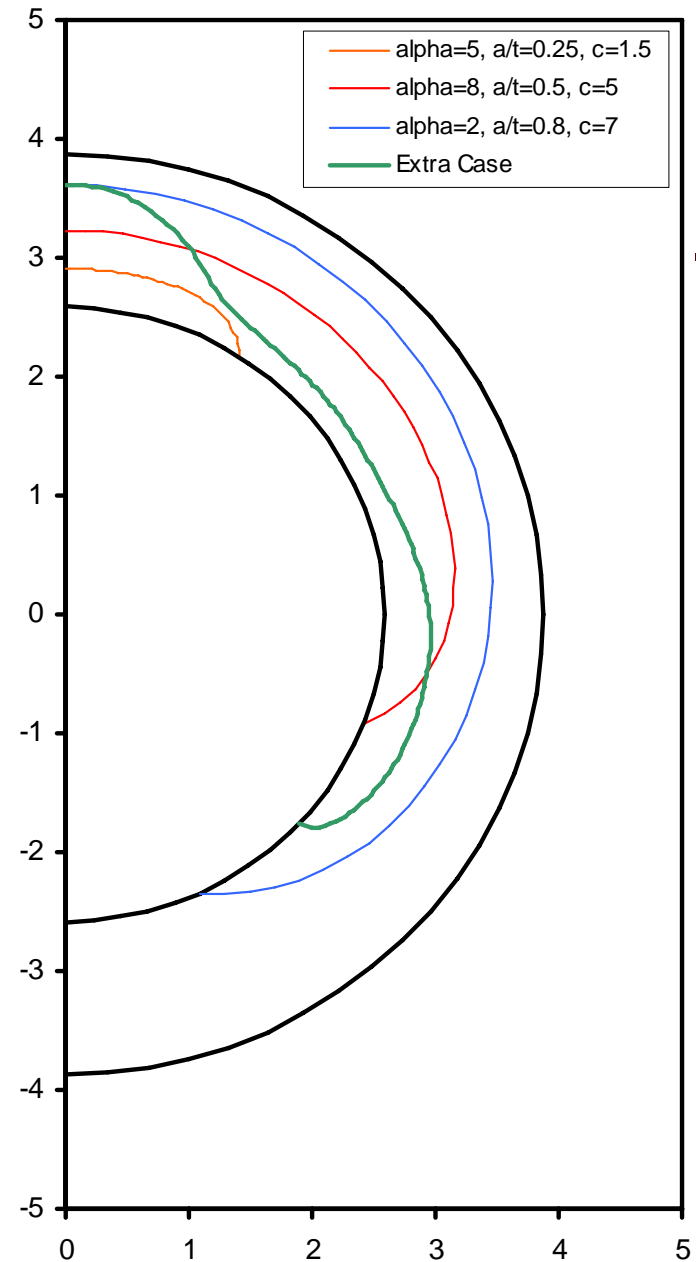
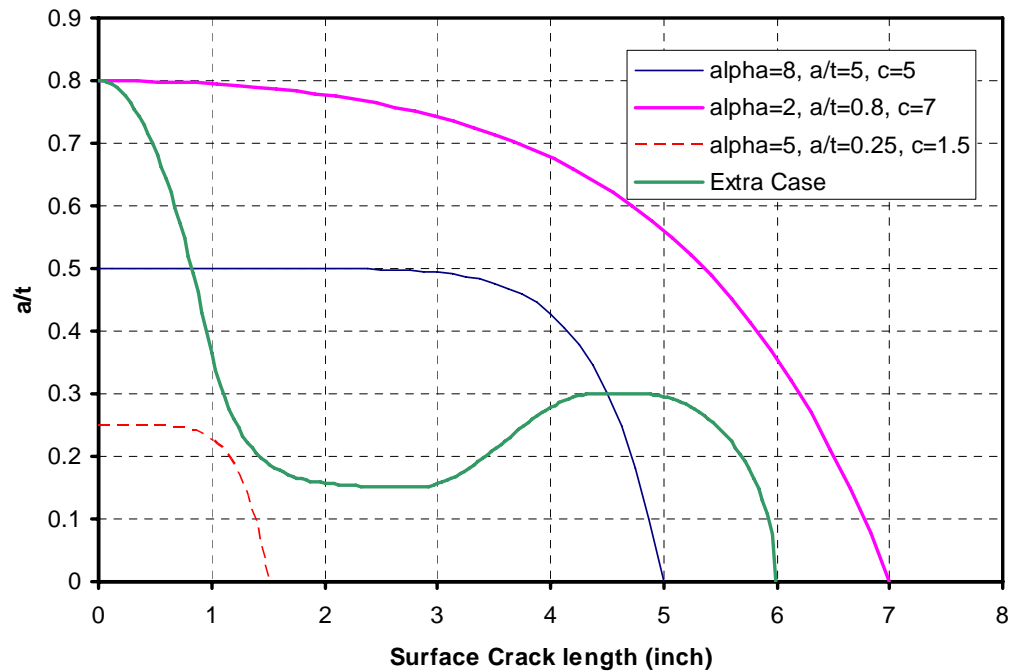
K Validation

Introduction

- FEACrack has been applied to generate K solutions for the three custom crack profiles suggested by EMC2
- Results not yet available for the fourth profile, which was suggested by DEI

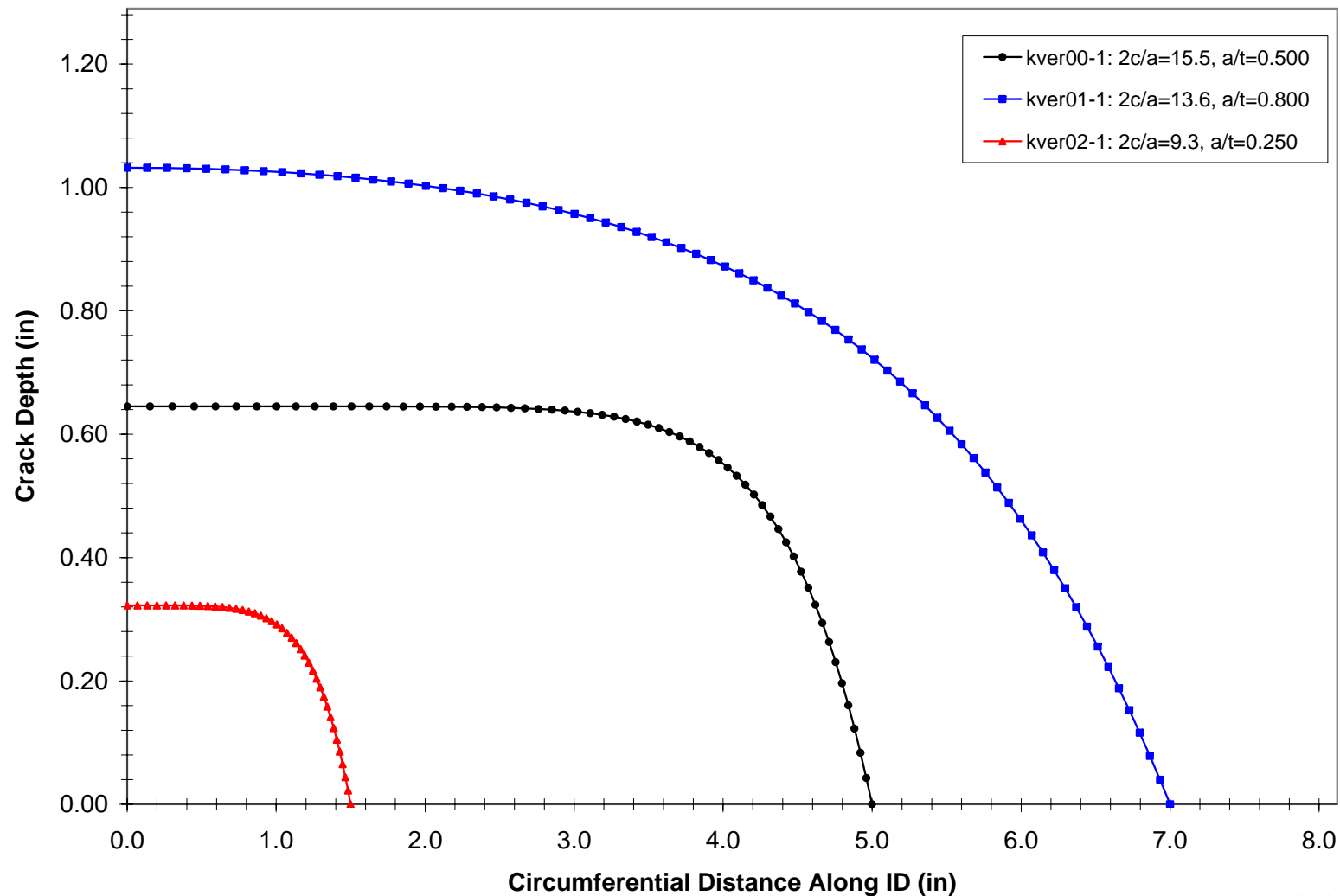
K Validation

Proposed Crack Profiles



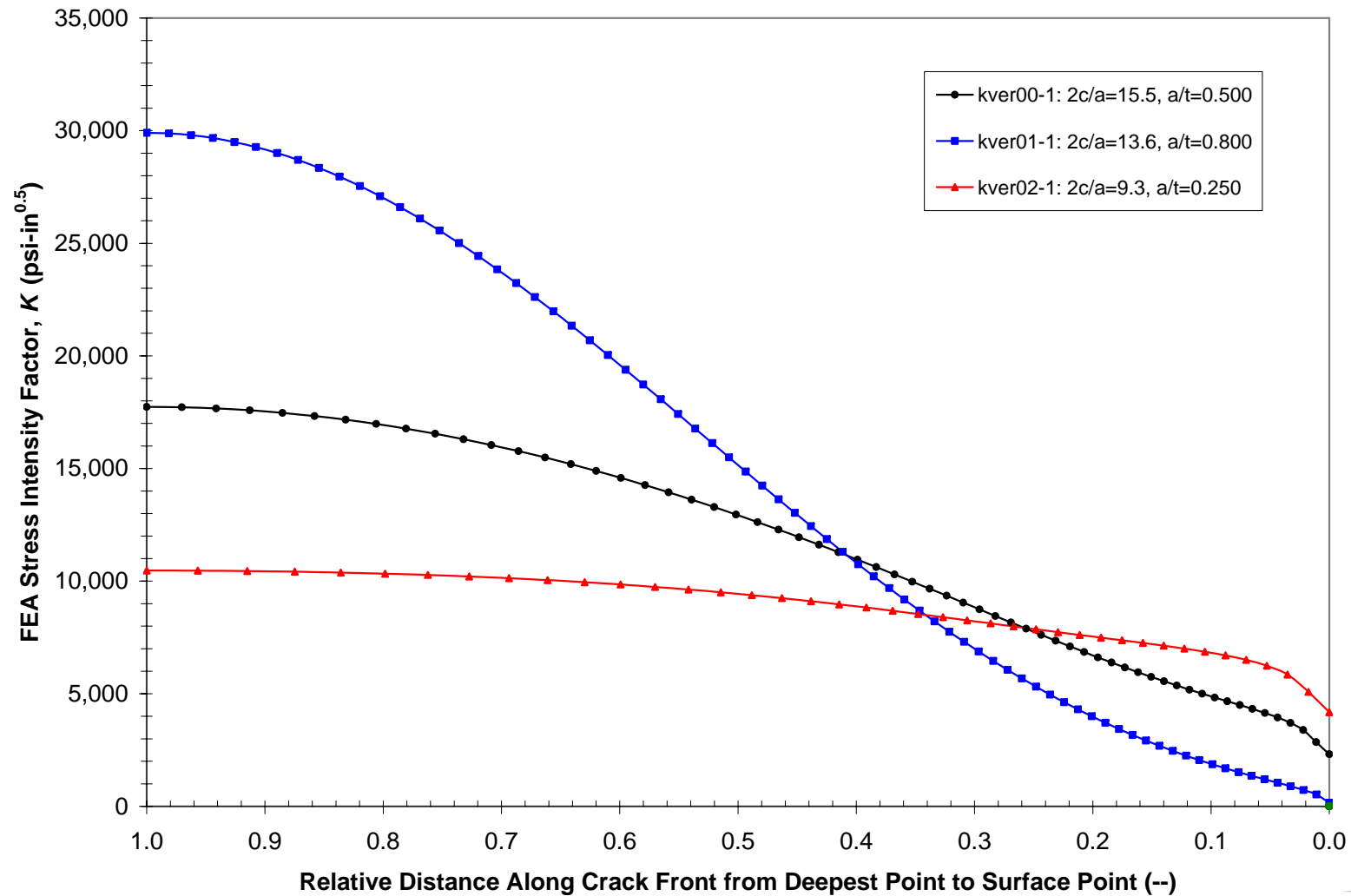
K Validation

Corner Node Positions Along Crack Front



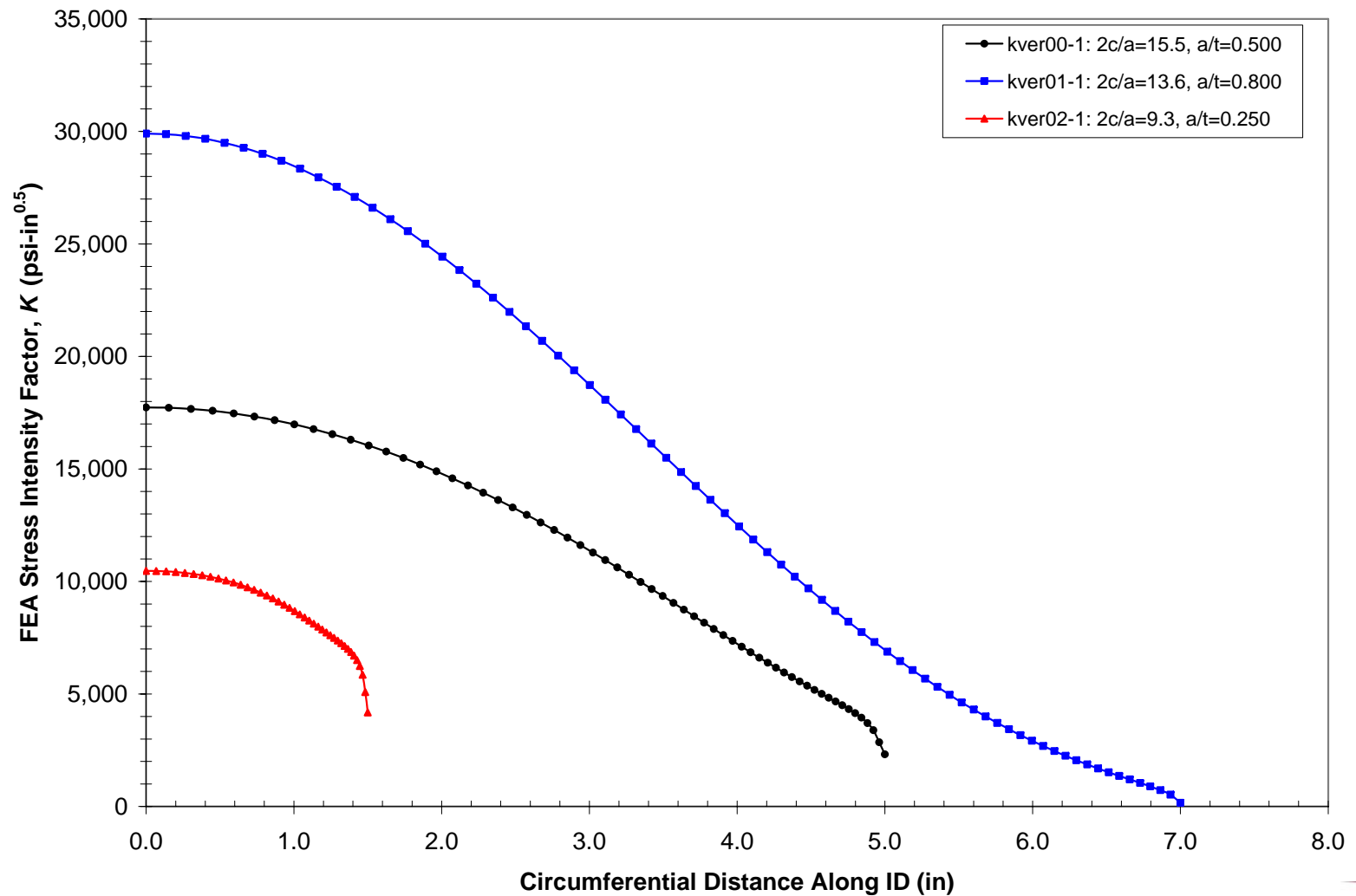
K Validation

K Result as Function of Relative Crack Front Position



K Validation

K Result as Function of Circumferential Position on ID



Model Convergence

Summary

- Previous results presented by DEI on May 8 showed about 7.5 years to through-wall penetration for Phase 1 calculation geometry and loads
 - Subsequent work shows increase in time from earlier results (~5.1 years) due mostly to slight change in WRS profile assumed
- Most recent comparisons between DEI and EMC2 results for Phase 1 calculation geometry and loads (including WRS) show close agreement in time to through-wall penetration
 - DEI time to through-wall: 5.36 years
 - EMC2 time to through-wall: 5.35 years
- Close agreement in independent models gives confidence that results are mathematically correct

Model Convergence

Summary (cont'd)

- Time to through-wall observed to be sensitive to WRS assumption, but time from detectable leakage to rupture expected to be much less sensitive to WRS assumption
 - Sensitivity of time to through-wall penetration with WRS due to importance of minimum in dependence of stress intensity factor at deepest point vs. crack depth
 - Profile at time of through-wall penetration observed to be less sensitive to WRS
- Case to explicitly demonstrate convergence using refined growth steps still to be completed
- Additional work has been completed investigating effect of spatial mesh refinement on temperature strain simulation of WRS

Update on Timeline of Activities

- WRS Modeling
- Validation Studies
- Leak-Rate Studies

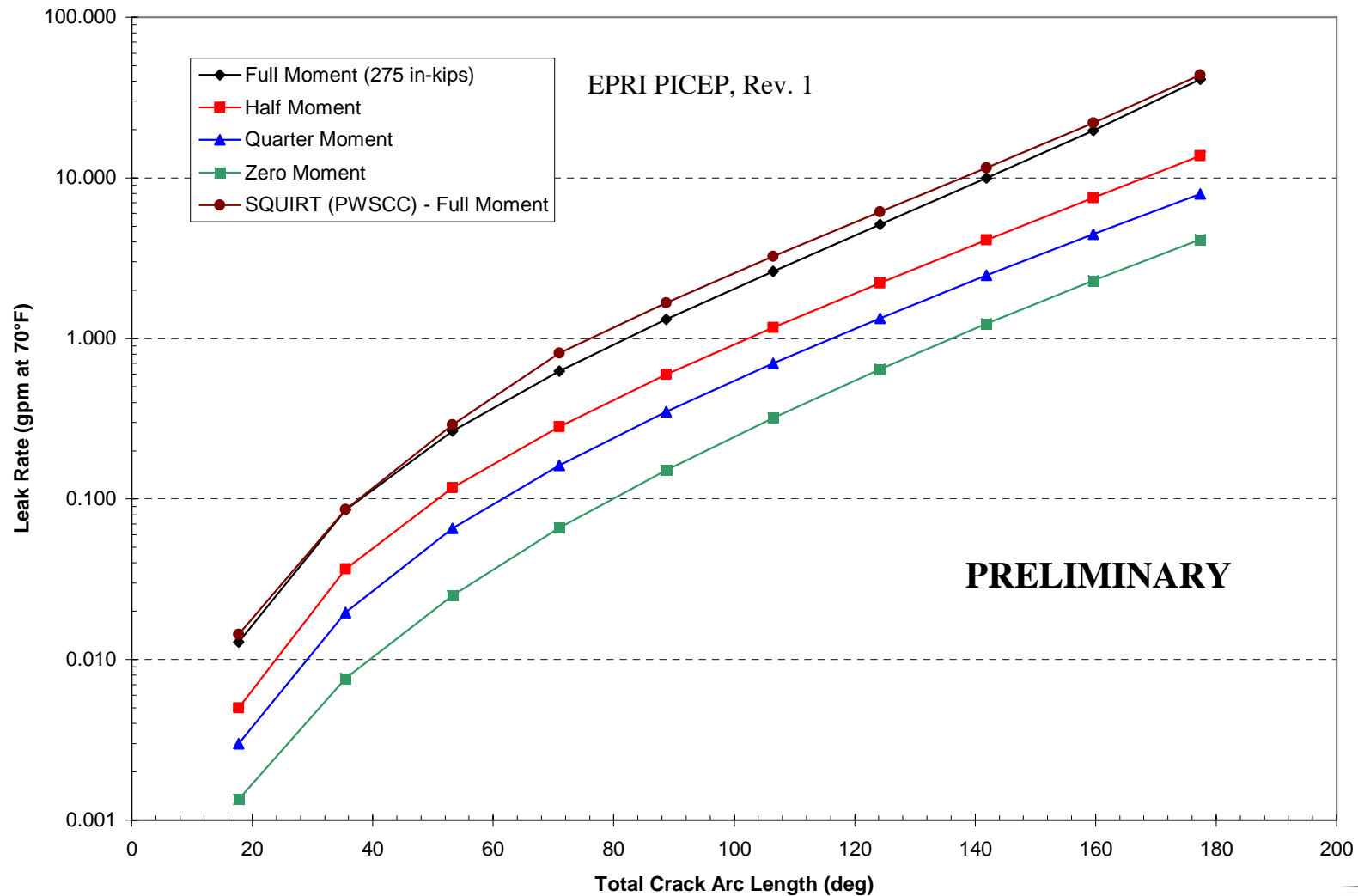
Leak Rate Calculations

Approach

- PICEP and SQUIRT software models are being applied using crack morphology parameters appropriate to intergranular nature of PWSCC
 - Wilkowski presentation at 2003 NRC Conference on Alloy 600 PWSCC in Gaithersburg, Maryland
- As a scoping tool, PICEP is being applied to calculate COD and leak rate as a function of assumed piping load
 - See example on next slide
- For each FEA crack growth progression case, the leak rate as a function of time will be calculated on the basis of the COD directly from the through-wall portion of the complex crack FEA model
 - The COD dependence through the wall thickness in the through-wall crack region will be examined to determine the controlling COD parameters

Leak Rate Calculations

Example Scoping Results for WC Relief Nozzle DM Weld



Status of NRC Confirmatory Research

- To be presented by NRC
 - K Validation
 - Model Convergence
 - Update on Timeline of Activities
 - WRS
 - Phase II Sensitivity Studies
 - Validation Studies
 - Leak-Rate Studies

Thursday Afternoon Agenda

- Presentation & Discussion of Proposed Sensitivity Matrix (Industry)
 - List of Sensitivity Matrix Cases that Industry will Evaluate
 - Loads/Geometries/WRS/CGR/Multiple Crack Growth

Proposed Sensitivity Matrix

Items Covered

- *Item 1.* Plant Specific Geometries
- *Item 2.* Plant Specific Loads
- *Item 3.* Proposed Weld Residual Stresses
 - Cracks growing in an axisymmetric WRS field
 - Cracks growing in an axisymmetric + repair WRS field
- *Item 4.* Crack Growth Rate Equation
- *Item 5.* Multiple Crack Growth Calculations
- Other Items
 - Initial flaw geometry
 - Redistribution of load given high WRS at ID surface
 - Crack inserted directly into the 3-dimensional DEI WRS FEA model

Proposed Sensitivity Matrix

Specific Matrix Parameters

Case

1. Model type: Cylindrical model or crack inserted into nozzle-to-safe-end WRS FEA Model
2. Dimensions case: Config 1a, 1b, 2a, 2b, 3, 4, 5, 6, 7, 8, 9
3. Load assumption: $P_m = x$; $P_b = y$
4. Welding residual stress assumption (WRS): for example axisymmetric 1, 2, 3 or repair case 1, 2, 3 or elastic-plastic redistribution simulation
5. Crack growth rate equation exponent on K: $n = 1.6$, or for example 1.3, 2.0
6. Initial flaw aspect ratio assumption: 6:1 part-arc, 21:1 part arc, 360° full-arc
7. Initial flaw shape factor: semi-ellipse, near uniform depth (high shape factor), low shape factor, or "natural" shape
8. Initial flaw depth: 26% or for example 10%, 40%

Proposed Sensitivity Matrix

Example Case

Case YY:

- Cylindrical model;
- Config 1a dimensions;
- $P_m = 3.5$ ksi, $P_b = 7.5$ ksi;
- axisymmetric WRS1;
- CGR $n = 1.6$;
- 21:1 initial flaw;
- natural shape;
- 26% initial depth

Proposed Sensitivity Matrix

Selectively Vary Parameters

1. **Model type:** Cylindrical model in most cases; crack inserted into nozzle-to-safe-end WRS FEA Model as a check in a few cases
2. **Dimensions case:** cover all cases but may combine some cases within nozzle type (S&R, spray, and surge) if justified by runs showing small sensitivity
3. **Load assumption:** Cover full range of P_b for each dimension case; expect small sensitivity to range of P_m for each dimension case
4. **Welding residual stress assumption (WRS):** must check sensitivity to various cases
5. **Crack growth rate equation exponent on K:** use $n = 1.6$ for most cases; for cases showing smallest margin also use statistical lower and upper bounds for n from MRP-115 database
6. **Initial flaw aspect ratio assumption:** concentrate on 21:1 part-arc flaw and 360° full-arc flaws
7. **Initial flaw shape factor:** only a few cases to confirm insensitivity to this
8. **Initial flaw depth:** only a few cases to confirm insensitivity to this

Proposed Sensitivity Matrix

Final Case Matrix

- Exact combinations of parameters depends on
 - Results from initial case runs
 - FEA WRS results
- Applying the simplified axisymmetric growth model presented on May 8 to eliminate those combinations that result in arrest at a relatively shallow depth from consideration
- Input from May 31 and June 1 meeting discussions

Proposed Sensitivity Matrix

Outputs

- Time from detectable leakage to rupture
 - Key parameter
 - Assuming normal loads
 - Assuming faulted loads for select cases
- Time from through-wall penetration to rupture
 - Can be compared to time of most recent bare metal visual examination
- Total time from initial flaw to rupture
 - Can be compared to operating age of each subject plant
- For some key cases, complete output parameters will be displayed in the report, as in the Phase 1 calculation

Proposed Sensitivity Matrix

Geometry and Load Combinations

Note: P_m in this table based on pressure stress $pD_o/4t$. Pressure stress $pD_i^2/(D_o^2-D_i^2)$ plus deadweight and secondary piping axial force and pressure on crack face to be used for crack growth.

Type	Design	# of nozzles	Loads					
			P_m		P_b		$P_b/(P_m+P_b)$	
			(ksi)		(ksi)		-	
			Min	Max	Min	Max	Min	Max
Safety and Relief Nozzles	1a	12	3.17	3.45	0.07	5.71	0.02	0.64
	1b	4	3.20	3.71	0.78	5.74	0.20	0.63
	2a	8	3.93	4.29	1.04	7.63	0.21	0.64
	2b	4	3.57	3.90	2.35	4.78	0.38	0.57
	3	7	3.16	3.24	0.00	6.70	0.00	0.67
Spray Nozzles	4	2	3.45	3.58	1.38	4.89	0.28	0.59
	5	3	4.00	4.20	1.12	4.75	0.21	0.54
	6	1	3.84	3.84	0.75	0.75	0.16	0.16
	7	2	2.76	3.05	1.16	4.80	0.30	0.61
Surge Nozzles	8	6	5.24	5.43	4.04	13.58	0.43	0.72
	9	2	4.92	5.06	6.65	14.55	0.57	0.74

Proposed Sensitivity Matrix

Initial Planned Matrix (slide 1/3)

Prelim Case #	Model Type	Nozzle Type	Geometry	Load Case			WRS Case	CGR Expon. n	Initial Flaw		
				Pm (ksi)	Pb (ksi)	Pb/(Pm+Pb)			2c/a	Shape Factor	Depth (%tw)
1	cylinder	S&R	Config 1a	typical	high	high	S&R no liner	1.6	21 or 360°	natural	26% or 10%
2	cylinder	S&R	Config 1a	typical	above arrest	above arrest	S&R no liner	1.6	21 or 360°	natural	26% or 10%
3	cylinder	S&R	Config 1b	typical	high	high	S&R no liner	1.6	21 or 360°	natural	26% or 10%
4	cylinder	S&R	Config 1b	typical	above arrest	above arrest	S&R no liner	1.6	21 or 360°	natural	26% or 10%
5	cylinder	S&R	Config 2a	typical	high	high	S&R with liner	1.6	21 or 360°	natural	26% or 10%
6	cylinder	S&R	Config 2a	typical	above arrest	above arrest	S&R with liner	1.6	21 or 360°	natural	26% or 10%
7	cylinder	S&R	Config 2b	typical	high	high	S&R with liner	1.6	21 or 360°	natural	26% or 10%
8	cylinder	S&R	Config 2b	typical	above arrest	above arrest	S&R with liner	1.6	21 or 360°	natural	26% or 10%
9	cylinder	S&R	Config 3	typical	high	high	S&R no liner	1.6	21 or 360°	natural	26% or 10%
10	cylinder	S&R	Config 3	typical	above arrest	above arrest	S&R no liner	1.6	21 or 360°	natural	26% or 10%
11	cylinder	spray	Config 4	typical	high	high	generic spray	1.6	21 or 360°	natural	26% or 10%
12	cylinder	spray	Config 4	typical	above arrest	above arrest	generic spray	1.6	21 or 360°	natural	26% or 10%
13	cylinder	spray	Config 5	typical	high	high	generic spray	1.6	21 or 360°	natural	26% or 10%
14	cylinder	spray	Config 5	typical	above arrest	above arrest	generic spray	1.6	21 or 360°	natural	26% or 10%
15	cylinder	spray	Config 6	typical	high	high	generic spray	1.6	21 or 360°	natural	26% or 10%
16	cylinder	spray	Config 6	typical	above arrest	above arrest	generic spray	1.6	21 or 360°	natural	26% or 10%
17	cylinder	spray	Config 7	typical	high	high	generic spray	1.6	21 or 360°	natural	26% or 10%
18	cylinder	spray	Config 7	typical	above arrest	above arrest	generic spray	1.6	21 or 360°	natural	26% or 10%
19	cylinder	surge	Config 8	typical	high	high	surge with fill-in weld	1.6	21 or 360°	natural	26% or 10%
20	cylinder	surge	Config 8	typical	above arrest	above arrest	surge with fill-in weld	1.6	21 or 360°	natural	26% or 10%
21	cylinder	surge	Config 9	typical	high	high	surge no fill-in weld	1.6	21 or 360°	natural	26% or 10%
22	cylinder	surge	Config 9	typical	above arrest	above arrest	surge no fill-in weld	1.6	21 or 360°	natural	26% or 10%

Proposed Sensitivity Matrix

Initial Planned Matrix (slide 2/3)

Prelim Case #	Model Type	Nozzle Type	Geometry	Load Case			WRS Case	CGR Expon. n	Initial Flaw		
				Pm (ksi)	Pb (ksi)	Pb/(Pm+Pb)			2c/a	Shape Factor	Depth (%tw)
23	cylinder	S&R	Config 1a	typical	high	high	S&R ID repair no liner	1.6	21 or 360°	natural	26% or 10%
24	cylinder	S&R	Config 1a	typical	above arrest	above arrest	S&R ID repair no liner	1.6	21 or 360°	natural	26% or 10%
25	cylinder	S&R	Config 2b	typical	high	high	S&R ID repair with liner	1.6	21 or 360°	natural	26% or 10%
26	cylinder	S&R	Config 2b	typical	above arrest	above arrest	S&R ID repair with liner	1.6	21 or 360°	natural	26% or 10%
27	cylinder	surge	Config 8	typical	high	high	surge ID repair with fill-in	1.6	21 or 360°	natural	26% or 10%
28	cylinder	surge	Config 8	typical	above arrest	above arrest	surge ID repair with fill-in	1.6	21 or 360°	natural	26% or 10%
29	cylinder	bound	bounding	typical	sens 1	sens 1	bounding	1.6	21 or 360°	natural	26% or 10%
30	cylinder	bound	bounding	typical	sens 2	sens 2	bounding	1.6	21 or 360°	natural	26% or 10%
31	cylinder	bound	bounding	typical	sens 3	sens 3	bounding	1.6	21 or 360°	natural	26% or 10%
32	cylinder	bound	bounding	typical	sens 4	sens 4	bounding	1.6	21 or 360°	natural	26% or 10%
33	cylinder	S&R	as-built 1	typical	bounding	bounding	bounding	1.6	21 or 360°	natural	26% or 10%
34	cylinder	S&R	as-built 2	typical	bounding	bounding	bounding	1.6	21 or 360°	natural	26% or 10%
35	cylinder	S&R	bounding S&R	low	bounding	bounding	bounding	1.6	21 or 360°	natural	26% or 10%
36	cylinder	S&R	bounding S&R	high	bounding	bounding	bounding	1.6	21 or 360°	natural	26% or 10%
37	cylinder	TBD	TBD	typical	bounding	bounding	effect of SS weld	1.6	21 or 360°	natural	26% or 10%
38	cylinder	S&R	bounding S&R	typical	bounding	bounding	safe end ID buildup	1.6	21 or 360°	natural	26% or 10%
39	cylinder	S&R	bounding S&R	typical	bounding	bounding	tweaked axisymmetric	1.6	21 or 360°	natural	26% or 10%
40	cylinder	S&R	bounding S&R	typical	bounding	bounding	tweaked ID repair	1.6	21 or 360°	natural	26% or 10%
41	cylinder	spray	bounding spray	typical	bounding	bounding	tweaked axisymmetric	1.6	21 or 360°	natural	26% or 10%
42	cylinder	surge	bounding surge	typical	bounding	bounding	tweaked axisymmetric	1.6	21 or 360°	natural	26% or 10%
43	cylinder	surge	bounding surge	typical	bounding	bounding	tweaked ID repair	1.6	21 or 360°	natural	26% or 10%

Proposed Sensitivity Matrix

Initial Planned Matrix (slide 3/3)

Prelim Case #	Model Type	Nozzle Type	Geometry	Load Case			WRS Case	CGR Expon. n	Initial Flaw		
				Pm (ksi)	Pb (ksi)	Pb/(Pm+Pb)			2c/a	Shape Factor	Depth (%tw)
44	cylinder	S&R	bounding S&R	typical	bounding	bounding	shortened "weld"	1.6	21 or 360°	natural	26% or 10%
45	cylinder	S&R	bounding S&R	typical	bounding	bounding	simulate e-p redistrib.	1.6	21 or 360°	natural	26% or 10%
46	cylinder	S&R	bounding S&R	typical	bounding	bounding	bounding	1.6	2	natural	26%
47	cylinder	S&R	bounding S&R	typical	bounding	bounding	bounding	1.6	6	natural	26%
48	cylinder	S&R	bounding S&R	typical	bounding	bounding	bounding	1.6	21	low	26%
49	cylinder	S&R	bounding S&R	typical	bounding	bounding	bounding	1.6	21	semi-ellipse	26%
50	cylinder	S&R	bounding S&R	typical	bounding	bounding	bounding	1.6	21	high	26%
51	cylinder	S&R	bounding S&R	typical	bounding	bounding	bounding	1.6	21	natural	15%
52	cylinder	S&R	bounding S&R	typical	bounding	bounding	bounding	1.6	21	natural	40%
53	cylinder	S&R	bounding S&R	typical	bounding	bounding	bounding	low	21 or 360°	natural	26% or 10%
54	cylinder	S&R	bounding S&R	typical	bounding	bounding	bounding	high	21 or 360°	natural	26% or 10%
55	cylinder	spray	bounding spray	typical	bounding	bounding	bounding	low	21 or 360°	natural	26% or 10%
56	cylinder	spray	bounding spray	typical	bounding	bounding	bounding	high	21 or 360°	natural	26% or 10%
57	cylinder	surge	bounding surge	typical	bounding	bounding	bounding	low	21 or 360°	natural	26% or 10%
58	cylinder	surge	bounding surge	typical	bounding	bounding	bounding	high	21 or 360°	natural	26% or 10%
59	nozzle	S&R	bounding S&R	typical	bounding	bounding	axsymmetric	1.6	21 or 360°	natural	26% or 10%
60	nozzle	S&R	bounding S&R	typical	bounding	bounding	ID repair case	1.6	21 or 360°	natural	26% or 10%
61	nozzle	surge	bounding surge	typical	bounding	bounding	axsymmetric	1.6	21 or 360°	natural	26% or 10%
62	nozzle	surge	bounding surge	typical	bounding	bounding	ID repair case	1.6	21 or 360°	natural	26% or 10%

Proposed Sensitivity Matrix

Geometry and Load Inputs

- *The following slides repeat the geometry and piping load information previously presented in order to support the sensitivity matrix discussions*

Nozzle Geometry for Subject Plants

Summary

- There are a total of 51 pressurizer DM welds of concern in the group of nine plants:
 - 35 safety and relief (S&R) nozzles (1 plant has only three S&R nozzles)
 - 8 surge nozzles (+1 already overlayed)
 - 8 spray nozzles (+1 examined by PDI process in 2005)
- Using design drawings, basic weld dimensions have been tabulated for the 51 subject welds:
 - Weld thickness
 - For welds with taper from LAS nozzle to safe end, thickness is based on average of design diameters at toe on nozzle and at toe on safe end
 - Liner or sleeve thickness not included in weld thickness for cases in which liner or sleeve is in direct contact with DM weld
 - Radius to thickness ratio (R_i/t) based on design inside diameter at weld and weld thickness per previous bullet
 - Approximate weld separation axial distance between root of DM weld and root of SS weld to piping

Nozzle Geometry for Subject Plants

Geometry Cases

- A review of design drawings for the nine plants indicates the following nozzle geometry cases:
 - S&R nozzles
 - Types 1a and 1b: W design without liner, connected to 6" pipe
 - Types 2a and 2b: W design with liner directly covering DM weld, connected to 6" pipe
 - Type 3: CE design (no liner), connected to 6" pipe
 - Spray nozzles
 - Type 4: W design with liner (does not extend to most of DM weld), connected to 4" pipe
 - Type 5: W design with liner directly covering DM weld, connected to 4" pipe
 - Type 6: W design without liner, connected to 6" pipe
 - Type 7: CE design (no liner, sleeve not extending to DM weld), connected to 4" pipe
 - Surge nozzles
 - Type 8: W design (sleeve directly covers fill-in weld under nozzle-to-safe-end weld), connected to 14" pipe
 - Type 9: CE design (sleeve not extending to DM weld), connected to 12" pipe

Nozzle Geometry and Repair History

PRELIMINARY Summary Table

Plant Code	Relief									Safety A								
	Design #	Piping NPS	Liner?	DM Weld t (in.)	DM Weld R _t /t	Weld Sep. (in.)	Butter Weld Repairs	ID Weld Repairs	OD Weld Repairs	Design #	Piping NPS	Liner?	DM Weld t (in.)	DM Weld R _t /t	Weld Sep. (in.)	Butter Weld Repairs	ID Weld Repairs	OD Weld Repairs
Plant A	1a	6"	N	1.29	2.0	2.2	NR	NR	NR	1a	6"	N	1.29	2.0	2.2	NR	NR	R4
Plant E	1a	6"	N	1.29	2.0	2.2	NR	NR	R	1a	6"	N	1.29	2.0	2.2	NR	NR	NR
Plant H	1a	6"	N	1.29	2.0	2.2	NR	NR	NR	1a	6"	N	1.29	2.0	2.2	NR	R	R
Plant B	2a	6"	Y	1.07	2.6	2.6	NR	NR	R1	2a	6"	Y	1.07	2.6	2.6	NR	NR	NR
Plant G	2a	6"	Y	1.07	2.6	2.6	NR	NR	NR	2a	6"	Y	1.07	2.6	2.6	NR	NR	NR
Plant C	2b	6"	Y	1.07	2.6	2.3	NR	NR	NR	2b	6"	Y	1.07	2.6	2.3	R		
Plant F	1b	6"	N	1.41	1.8	3.3	NR	NR	NR	1b	6"	N	1.41	1.8	3.3	R		
Plant D	3	6"	N	1.41	1.8	6.8	NR	NR	NR	3	6"	N	1.41	1.8	6.8	R	NR	NR
Plant I	3	6"	N	1.41	1.8	6.8	N/A	N/A	N/A	3	6"	N	1.41	1.8	6.8	N/A	N/A	N/A
Plant J	1a	6"	N	1.29	2.0	2.2	Rx5	R1	R1	1a	6"	N	1.29	2.0	2.2	R	R2	NR

Notes:

1. For Designs #2a, #2b, and #5, liner directly covers DM weld.
2. For Design #4, liner does not extend to most of DM weld.
3. For Designs #4, #5, and #6, sleeve covers but does not contact DM weld.
4. For Design #8, sleeve directly covers DM weld.
5. For Designs #7 and #9, sleeve does not extend to DM weld.
6. NR = No weld repairs reported
7. Rn = Repairs reported (n indicates number of defect or repaired areas if reported; "x" indicates repeat weld repair operations)
8. N/A = Results for fabrication records review not available
9. Weld repair entries for Plants C and F are preliminary.
10. All pressurizer nozzle DM welds in Plant H are reported to be Alloy 82, not Alloy 82/182.

Nozzle Geometry and Repair History

PRELIMINARY Summary Table (cont'd)

Plant Code	Safety B									Safety C								
	Design #	Piping NPS	Liner?	DM Weld t (in.)	DM Weld R _h /t	Weld Sep. (in.)	Butter Weld Repairs	ID Weld Repairs	OD Weld Repairs	Design #	Piping NPS	Liner?	DM Weld t (in.)	DM Weld R _h /t	Weld Sep. (in.)	Butter Weld Repairs	ID Weld Repairs	OD Weld Repairs
Plant A	1a	6"	N	1.29	2.0	2.2	NR	R1	NR	1a	6"	N	1.29	2.0	2.2	NR	NR	NR
Plant E	1a	6"	N	1.29	2.0	2.2	NR	NR	NR	1a	6"	N	1.29	2.0	2.2	NR	R	NR
Plant H	1a	6"	N	1.29	2.0	2.2	NR	NR	NR	1a	6"	N	1.29	2.0	2.2	NR	NR	NR
Plant B	2a	6"	Y	1.07	2.6	2.6	NR	NR	NR	2a	6"	Y	1.07	2.6	2.6	NR	NR	NR
Plant G	2a	6"	Y	1.07	2.6	2.6	NR	NR	NR	2a	6"	Y	1.07	2.6	2.6	NR	NR	NR
Plant C	2b	6"	Y	1.07	2.6	2.3	R			2b	6"	Y	1.07	2.6	2.3	R		
Plant F	1b	6"	N	1.41	1.8	3.3	NR	NR	NR	1b	6"	N	1.41	1.8	3.3	NR	NR	NR
Plant D	3	6"	N	1.41	1.8	6.8	NR	NR	NR	3	6"	N	1.41	1.8	6.8	NR	NR	NR
Plant I	3	6"	N	1.41	1.8	6.8	N/A	N/A	N/A	No Safety C								
Plant J	1a	6"	N	1.29	2.0	2.2	NR	R6x2	NR	1a	6"	N	1.29	2.0	2.2	NR	NR	NR

Notes:

1. For Designs #2a, #2b, and #5, liner directly covers DM weld.
2. For Design #4, liner does not extend to most of DM weld.
3. For Designs #4, #5, and #6, sleeve covers but does not contact DM weld.
4. For Design #8, sleeve directly covers DM weld.
5. For Designs #7 and #9, sleeve does not extend to DM weld.
6. NR = No weld repairs reported
7. Rn = Repairs reported (n indicates number of defect or repaired areas if reported; "x" indicates repeat weld repair operations)
8. N/A = Results for fabrication records review not available
9. Weld repair entries for Plants C and F are preliminary.
10. All pressurizer nozzle DM welds in Plant H are reported to be Alloy 82, not Alloy 82/182.

Nozzle Geometry and Repair History

PRELIMINARY Summary Table (cont'd)

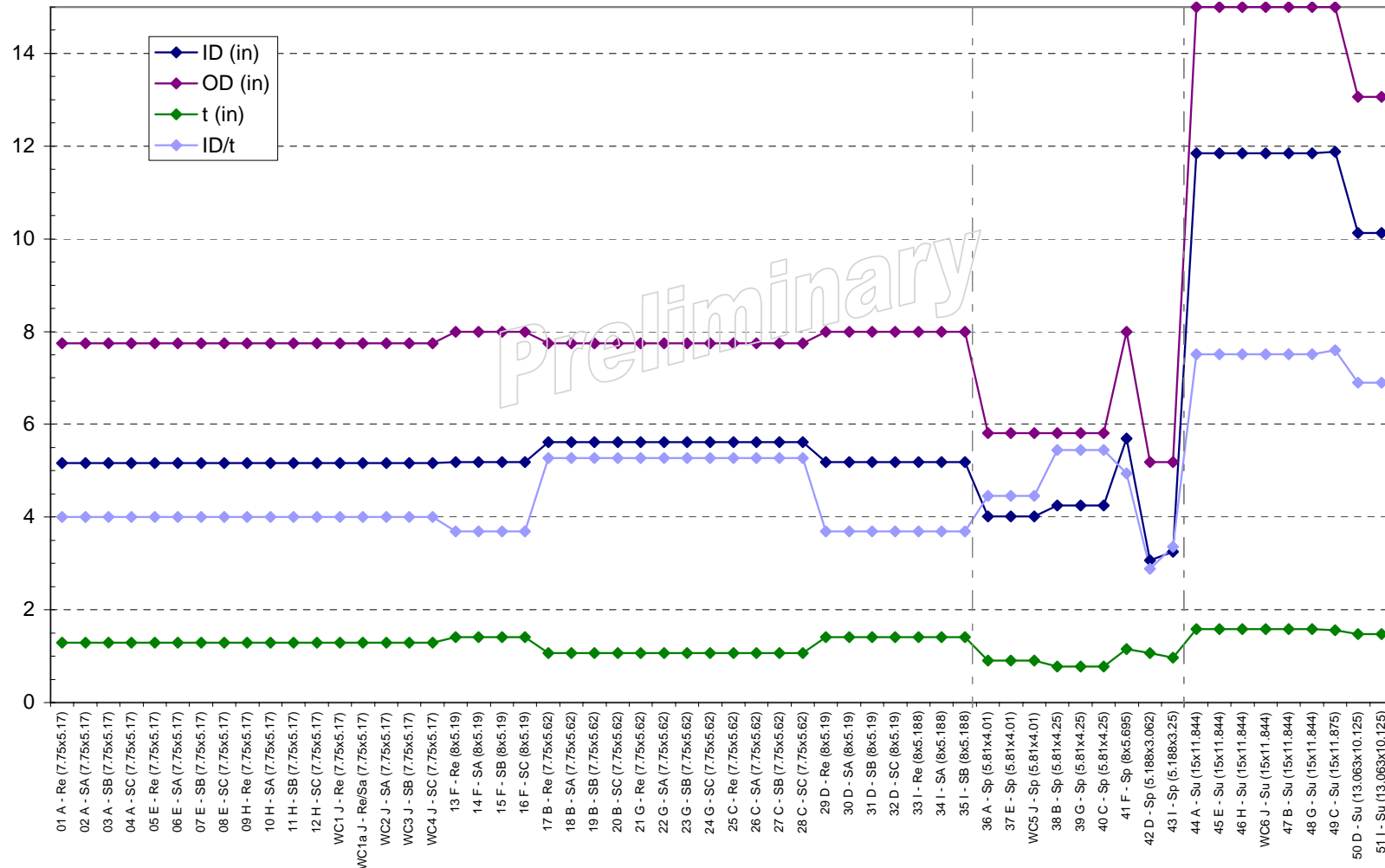
Plant Code	Spray (all have thermal sleeve)									Surge (all have thermal sleeve)								
	Design #	Piping NPS	Liner?	DM Weld t (in.)	DM Weld R _t /t	Weld Sep. (in.)	Butter Weld Repairs	ID Weld Repairs	OD Weld Repairs	Design #	Piping NPS	Liner?	DM Weld t (in.)	DM Weld R _t /t	Weld Sep. (in.)	Butter Weld Repairs	ID Weld Repairs	OD Weld Repairs
Plant A	4	4"	Y	0.90	2.2	~2.3	NR	NR	NR	8	14"	N	1.58	3.8	3.4	NR	R5	R3
Plant E	4	4"	Y	0.90	2.2	~2.3	R	NR	R	8	14"	N	1.58	3.8	3.4	NR	R3	NR
Plant H	Already PDI examined									8	14"	N	1.58	3.8	3.4	NR	NR	NR
Plant B	5	4"	Y	0.78	2.7	2.2	NR	NR	NR	8	14"	N	1.58	3.8	3.4	R1	R1x2	R2
Plant G	5	4"	Y	0.78	2.7	2.2	NR	NR	NR	8	14"	N	1.58	3.8	3.4	NR	NR	NR
Plant C	5	4"	Y	0.78	2.7	~2.2	R			8	14"	N	1.56	3.8	3.5	NR	NR	NR
Plant F	6	6"	N	1.15	2.5	3.6	NR	NR	NR	Already structural overlaid								
Plant D	7	4"	N	1.06	1.4	3.3	NR	NR	NR	9	12"	N	1.47	3.4	3.0	NR	NR	NR
Plant I	7	4"	N	1.06	1.4	3.3	N/A	N/A	N/A	9	12"	N	1.47	3.4	3.0	N/A	N/A	N/A
Plant J	4	4"	Y	0.90	2.2	~2.3	R	NR	NR	8	14"	N	1.58	3.8	3.4	R2	R1	NR

Notes:

1. For Designs #2a, #2b, and #5, liner directly covers DM weld.
2. For Design #4, liner does not extend to most of DM weld.
3. For Designs #4, #5, and #6, sleeve covers but does not contact DM weld.
4. For Design #8, sleeve directly covers DM weld.
5. For Designs #7 and #9, sleeve does not extend to DM weld.
6. NR = No weld repairs reported
7. Rn = Repairs reported (n indicates number of defect or repaired areas if reported; "x" indicates repeat weld repair operations)
8. N/A = Results for fabrication records review not available
9. Weld repair entries for Plants C and F are preliminary.
10. All pressurizer nozzle DM welds in Plant H are reported to be Alloy 82, not Alloy 82/182.

Nozzle Geometry for Subject Plants

Basic Weld Dimensions



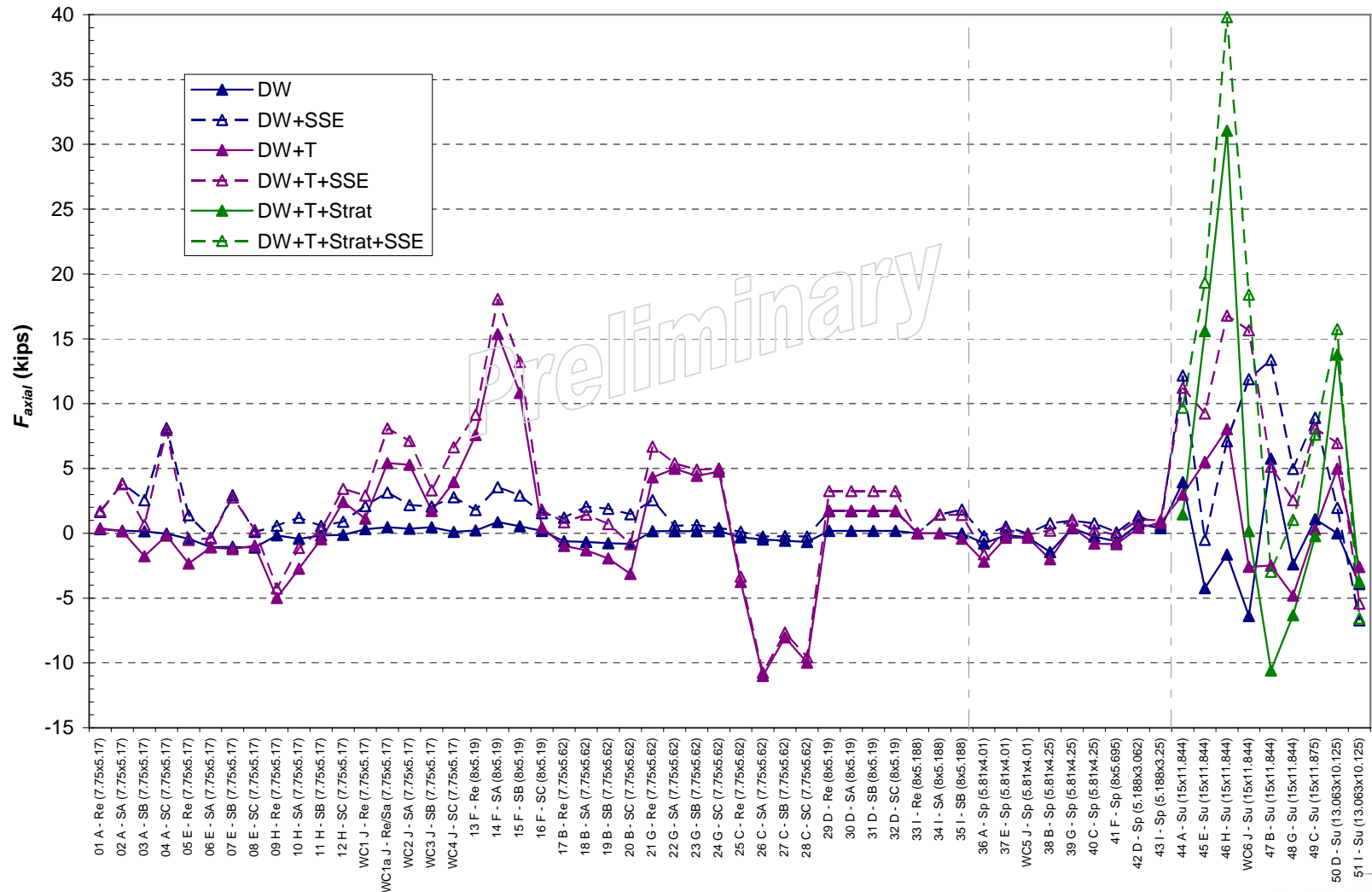
Plant-Specific Piping Loads

Approach

- Design pipe loads have now been collected for each of the 51 subject welds
- Differences in pipe axial force and moment loads have multiple effects on the relative crack growth rate in the radial and circumferential directions, as well as an effect on critical crack size
- Therefore, 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
 - Range of ratio of bending to total stress loading, $P_b/(P_m+P_b)$
 - Crack growth loads include dead weight and normal thermal pipe expansion loads (and normal thermal stratification loads in case of surge nozzles)
 - Length of thermal strain applied to simulate WRS will be varied

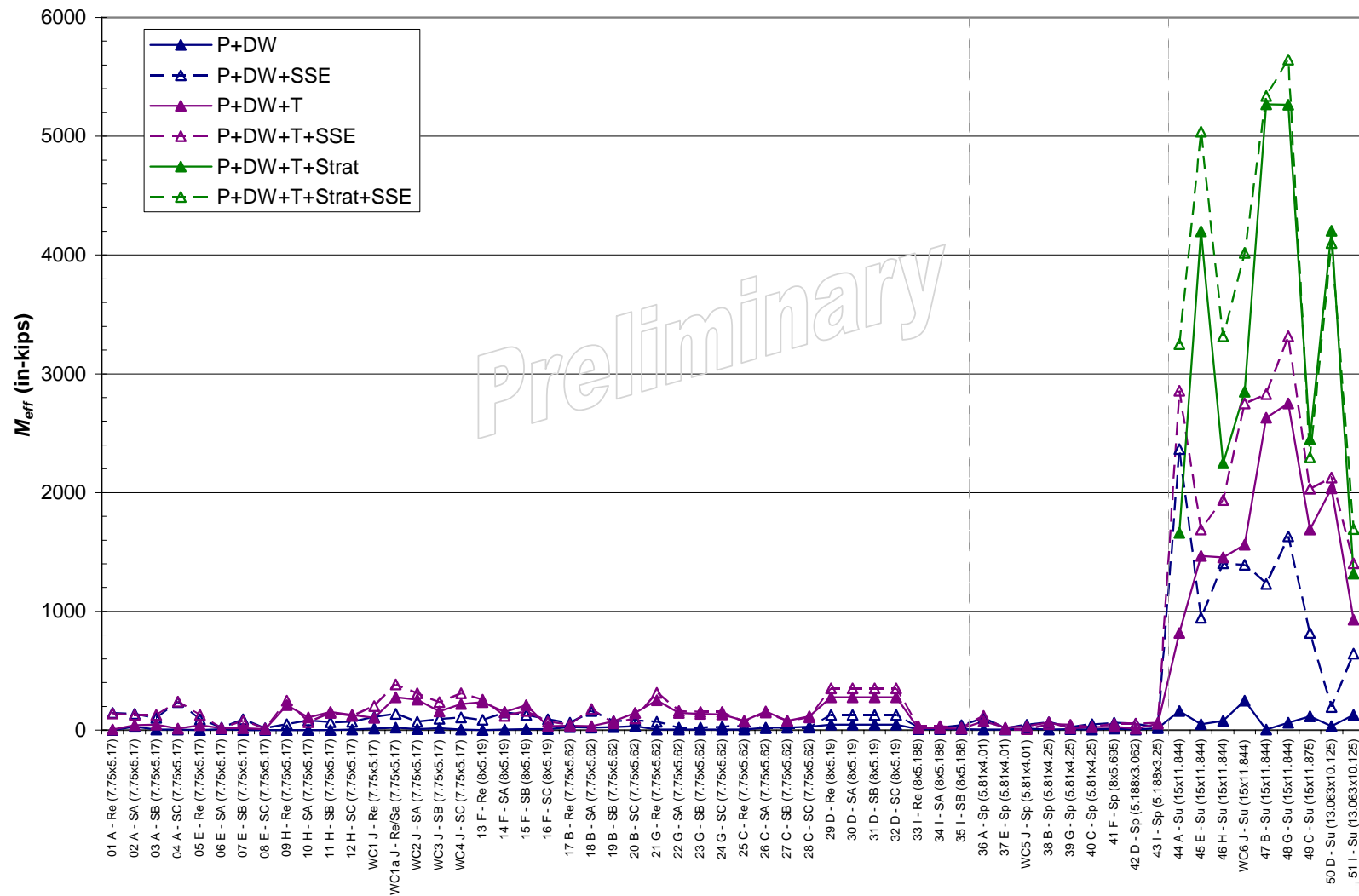
Plant-Specific Piping Loads

Nominal Axial Piping Loads (Not Including Endcap Pressure Load)



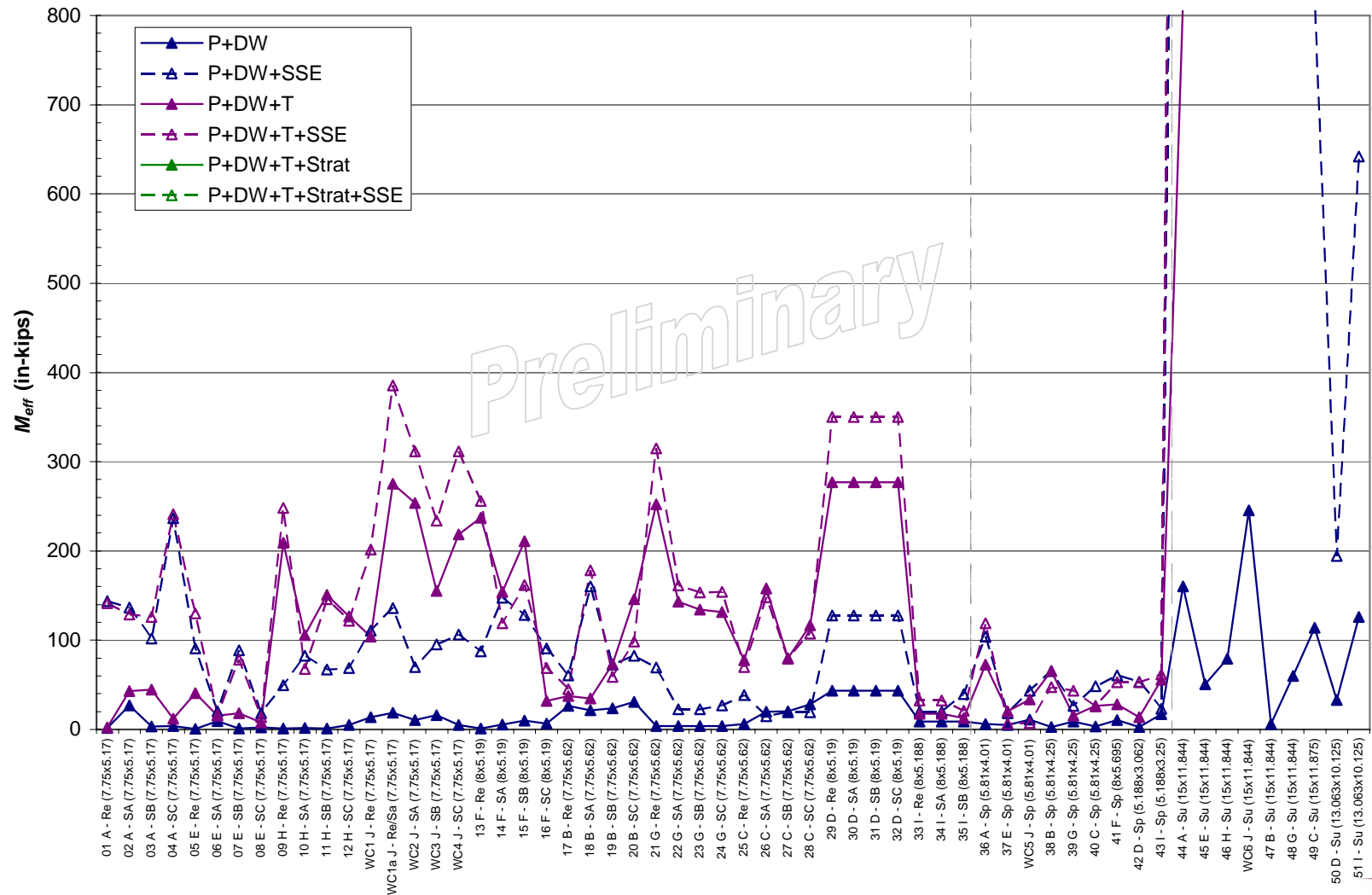
Plant-Specific Piping Loads

Nominal Effective Bending Moment Load (Full Scale)



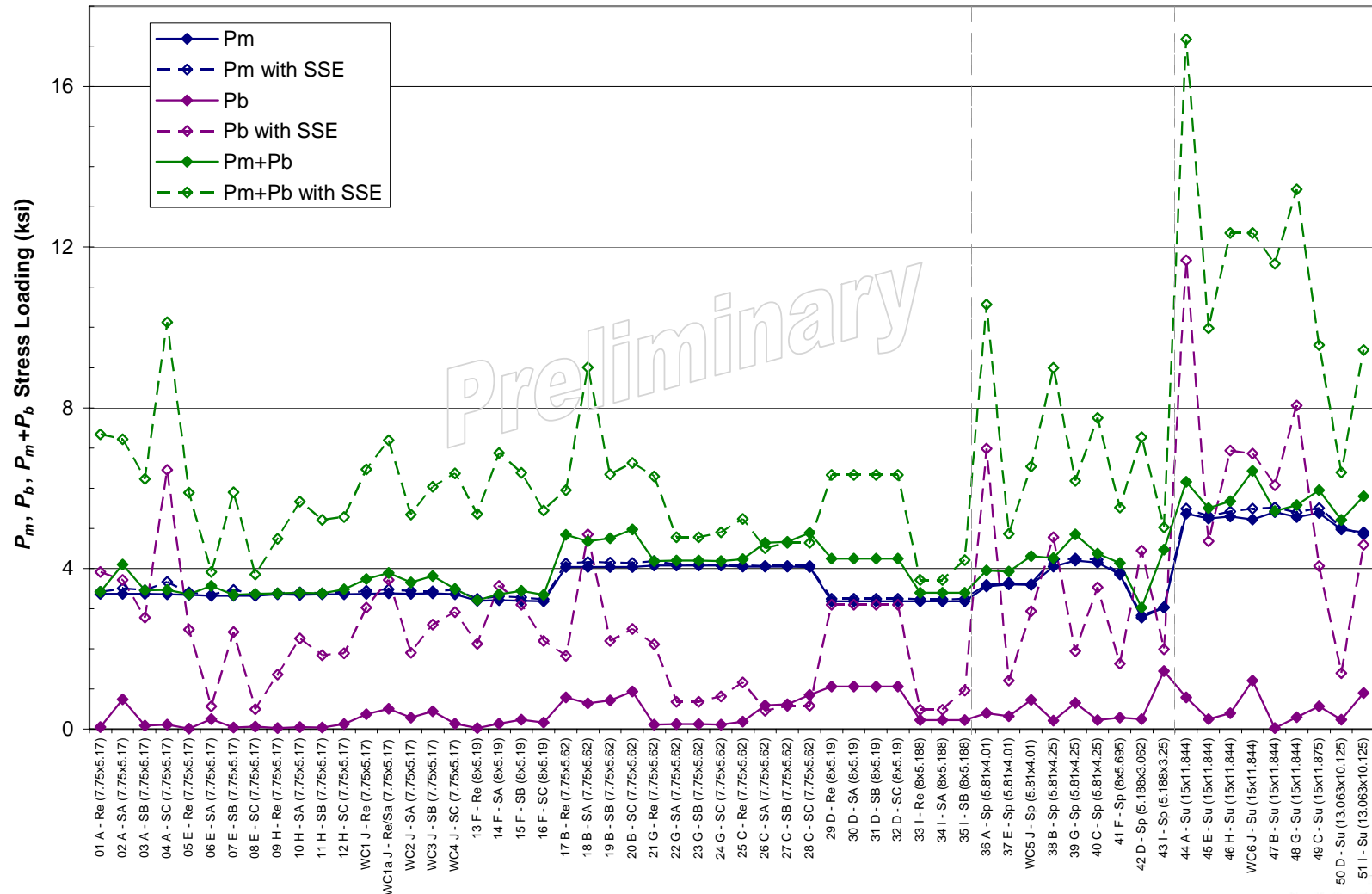
Plant-Specific Piping Loads

Nominal Effective Bending Moment Load (Partial Scale)



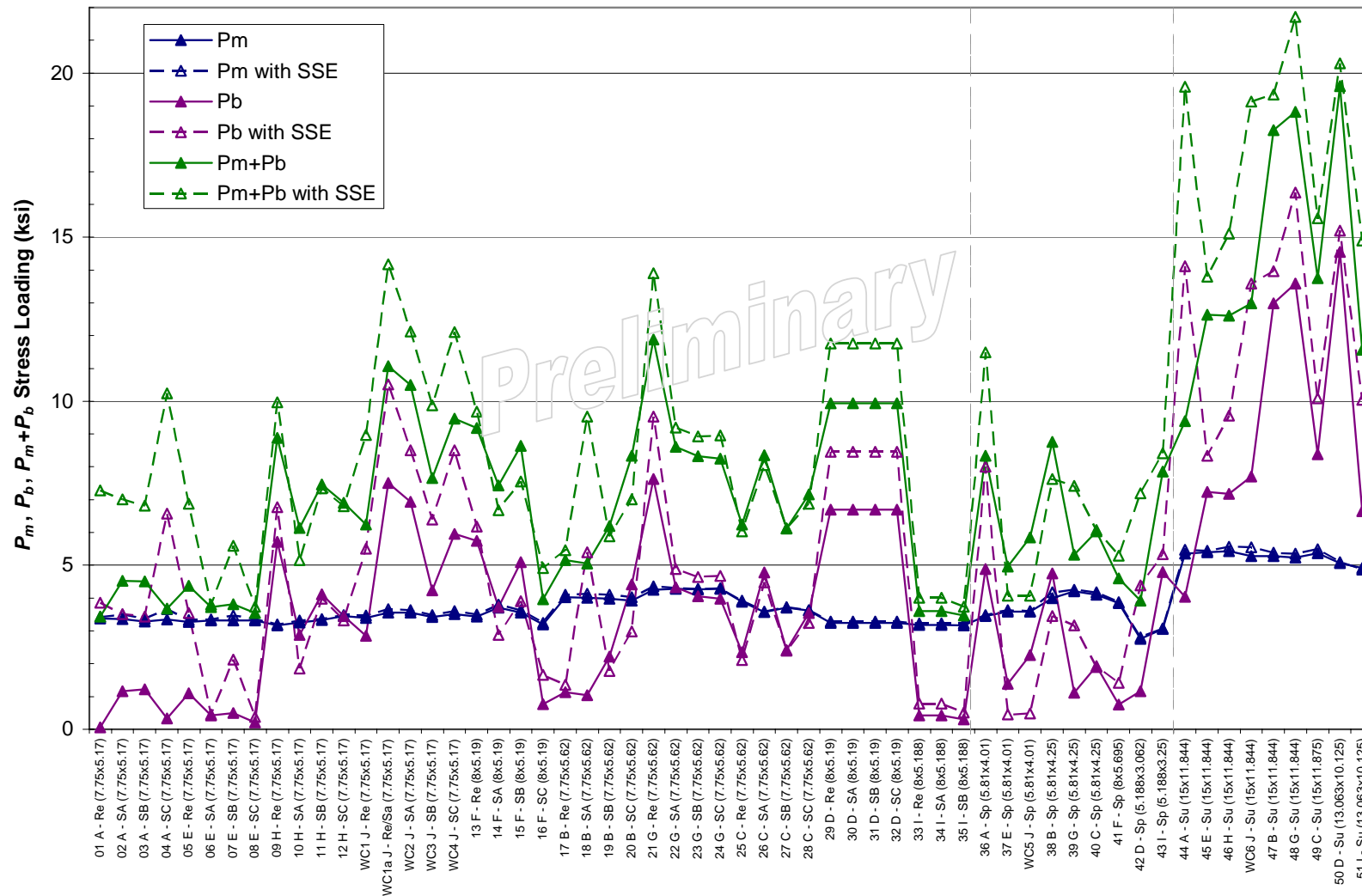
Plant-Specific Piping Loads

ASME Code Nominal Stress Loading for Pressure and Dead Weight Loading



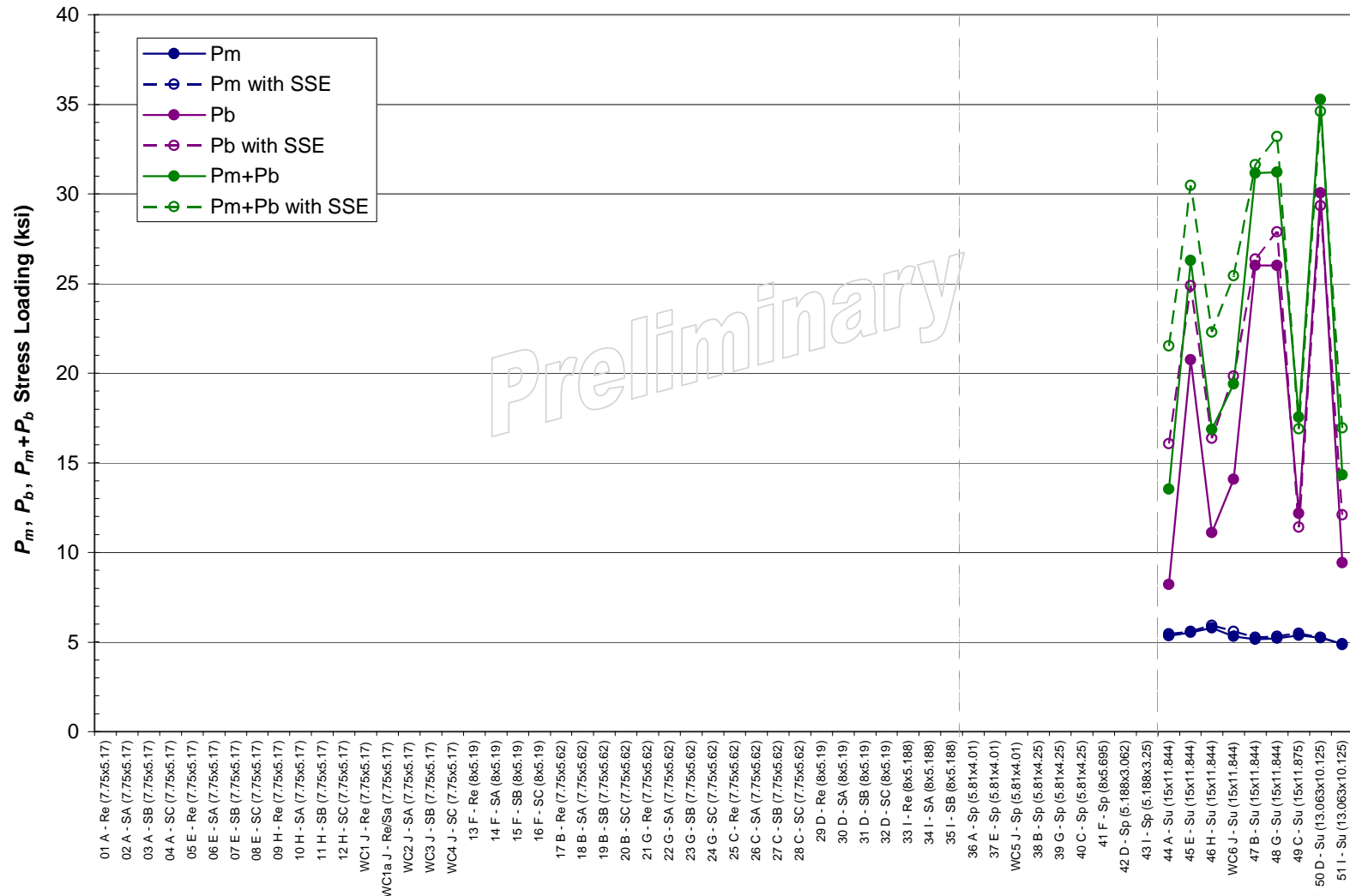
Plant-Specific Piping Loads

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



Plant-Specific Piping Loads

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



Friday Agenda

- Discussion of Proposed Sensitivity Matrix (Industry & NRC)
- Proposed Acceptance Criteria and Safety Factors (Industry)
- Plans for next meeting(s) (Industry & NRC)
- Meeting Summary and Conclusions (Industry & NRC)

Discussion of Proposed Sensitivity Matrix

- Review of Thursday Discussions

Acceptance Criteria and Safety Factors

Topics

- Background
 - NRC comment in March 5 letter
 - ASME Section XI
 - LBB assessments (NUREG-0800 SRP 3.6.3, etc.)
- SF considerations for subject evaluations
 - Short-term implementation issues
 - Efforts addressing uncertainties
 - Modeling conservatisms
 - Operating ages of subject plants
- Conclusions
 - Summary
 - Acceptance criteria under development

Acceptance Criteria and Safety Factors

NRC Comment in March 5 Letter

- "Safety Factor. The prior industry and NRC staff fracture mechanics analyses did not consider safety factors in their crack stability analyses. The American Society of Mechanical Engineers Boiler and Pressure Vessel Code requires the use of a safety factor of 3 to the applied stress intensity factor to determine crack stability under normal load conditions for a deterministic analysis. The safety factor is required even for a bounding analysis because there are uncertainties with all the input variables, and there are some things that are not accounted for in the deterministic analyses. Industry should consider the use of a safety factor to cover uncertainties in these analyses including the estimation of leakage."

Acceptance Criteria and Safety Factors

ASME Section XI

- ASME Section XI uses a safety factor on load for crack stability in evaluations for continued service of actual detected cracks
 - Recent code versions use factor of 2.7 for normal loads (Service Level A)
 - Previous code versions use factor of 3.0 for normal loads
 - Reduced factors are listed for infrequent loads (Service Levels B, C, and D)
- Such Section XI evaluations do not customarily include extensive sensitivity studies of calculation input parameters

Acceptance Criteria and Safety Factors

LBB Evaluations (NUREG-0800 SRP 3.6.3, etc.)

- For regulatory LBB assessments, SFs are traditionally applied to the detection leak rate and through-wall critical crack length
 - SF of 10 on detection leak rate
 - SF of 2.0 on through-wall critical crack length
 - SF of 1.4 on load for crack stability
- Such LBB assessments do not customarily include extensive sensitivity studies of calculation input parameters
- Such LBB assessments are intended to cover operation through end of licensing period

Acceptance Criteria and Safety Factors

Short-term Implementation Issue

- The question at hand is whether detailed crack growth, leak rate, and crack stability calculations demonstrate sufficiently high assurance of detection of leakage prior to rupture to support orderly timing of mitigation or first PDI examination at soonest refueling outage opportunity
 - 2 to 5 months after preferred implementation date of 12/31/2007
- This type of short-term implementation issue is different than
 - long-term assessments such as regulatory LBB
 - evaluations of actual detected flaws for continued operation

Acceptance Criteria and Safety Factors

Efforts Addressing Uncertainties

- The current effort is explicitly addressing various modeling uncertainties in a robust manner in order to reduce analysis uncertainties:
 - Explicit consideration of dimensions and loads for each subject weld
 - Inclusion of piping torsion load as part of crack growth driver
 - Effect of as-built dimensions vs. design dimensions
 - Sensitivity to various assumed welding residual stress profiles
 - Welding residual stress distributions based on weld repair data collected for subject welds
 - Potential effect of SS weld on stresses in DM weld
 - Effect of adjacent minor welds such as sleeve fill-in weld and liner fillet weld
 - Effect of uncertainty in crack growth rate equation K exponent
 - Effect of uncertainty in crack growth rate power-law constant
 - Consideration of initial cracks with high length-to-depth aspect ratios and initial 360° full-arc cracks

Acceptance Criteria and Safety Factors

Efforts Addressing Uncertainties (cont'd)

- Effect of uncertainty in initial flaw shape
- Sensitivity cases including detailed geometry and Q-stress load not usually considered
- Explicit consideration of non-leaking (i.e., surface) portion of crack in crack stability calculations
- Use of crack stability model for arbitrary crack shape rather than for idealized crack geometries
- NSC calculations based on flow strength of safe end material (assumes crack located near safe end, unlike apparent locations of WC indications and expected plane of maximum welding residual stress)
- Flow stress based on average of yield and ultimate strengths
- Detailed consideration of applicability of EPFM failure mode
- Detailed consideration of appropriate treatment of secondary stresses
- Consideration of potential effect of local ligament collapse
- Leak rate calculations using two standard industry codes
- Leak rate calculations based on COD from FEA rather than standard COD expressions for simplified loading assumption
- Verification and validation activities

Acceptance Criteria and Safety Factors

Modeling Conservatism

- Other modeling simplifications have been made, so no credit is conservatively taken for:
 - Tendency for finger-like crack growth in weld metal materials in through-wall direction
 - Tendency for crack initiation to be associated with weld repairs, which tend to drive cracks through-wall
 - Likely beneficial effect of weld start-stops on WRS field
 - 15 of 51 subject welds having liners (which are intended to keep material under the liner sealed from primary fluid) that cover the DM weld
 - Cracking through thickness of the liner fillet weld may be required prior to initiation of cracking in main DM weld
 - Likely temperature of spray nozzle DM welds significantly below pressurizer saturation temperature due to cooling from normal continuous flow in spray line
 - Possible nonzero stress intensity factor threshold for growth
 - Lower crack growth rate for growth perpendicular to dendrite solidification direction (best-estimate factor of 2.0 from MRP-115)

Acceptance Criteria and Safety Factors

Operating Ages of Subject Plants

- Operating age is a measure of effective degradation time
 - All subject pressurizers and Wolf Creek operate at the same nominal pressure and temperature
- Wolf Creek accumulated 150,000 operating hours to February 1, 2006
- Eight of nine subject plants have lower operating age to 2/1/2006 compared to Wolf Creek:
 - 95,000 hrs
 - 96,000 hrs
 - 118,000 hrs
 - 119,000 hrs
 - 129,000 hrs
 - 140,000 hrs
 - 142,000 hrs
 - 147,000 hrs
 - 154,000 hrs

Acceptance Criteria and Safety Factors

Conclusions – Summary

- It is appropriate that analyses demonstrate a high and sufficient level of assurance given possibility of circumferential flaws
- This short-term implementation issue is different than long-term safety evaluations or disposition of actual detected growing flaws
- Extensive consideration of analysis uncertainties and modeling conservatisms reduce the effect of analysis uncertainties
- Operating ages of subject plants are generally less than that for Wolf Creek
 - This effect tends to lower probability of crack initiation in subject plants
 - However, time for crack initiation not explicitly credited in the type of leakage prior to rupture calculation being performed

Acceptance Criteria and Safety Factors

Conclusions – Acceptance Criteria Under Development

- Acceptance criteria are currently under development for this project:
 - Calculated time between leak detection and critical crack is main assessment parameter
 - There is a high confidence of leak detection and plant shutdown within 7 days after the leak rate reaches 0.25 gpm
 - A margin factor >1 on the calculated leak rate is under consideration to address the uncertainty in the best-estimate leak rate predicted by the leak rate codes
 - Given extensive consideration of analysis uncertainties and modeling conservatisms, a margin factor of 1 on critical crack size may be appropriate
 - A secondary assessment parameter is the time between the initial crack and the critical crack, which can be compared to the operating age of each subject weld

Plans for Next Meeting(s)

- Previously tentatively scheduled meeting:
 - June 19 meeting: Present Phase II results
- Evening of Monday, June 11 is a potential opportunity for meeting around the EPRI Alloy 600 conference in Atlanta

Meeting Summary and Conclusions

- Industry
- NRC

Westinghouse and CE Pressurizer Nozzle Fabrication Detail

Warren Bamford & Cameron Martin

Wolf Creek Task Group Meeting
May 31 – June 1, 2007

Westinghouse Design Pressurizer

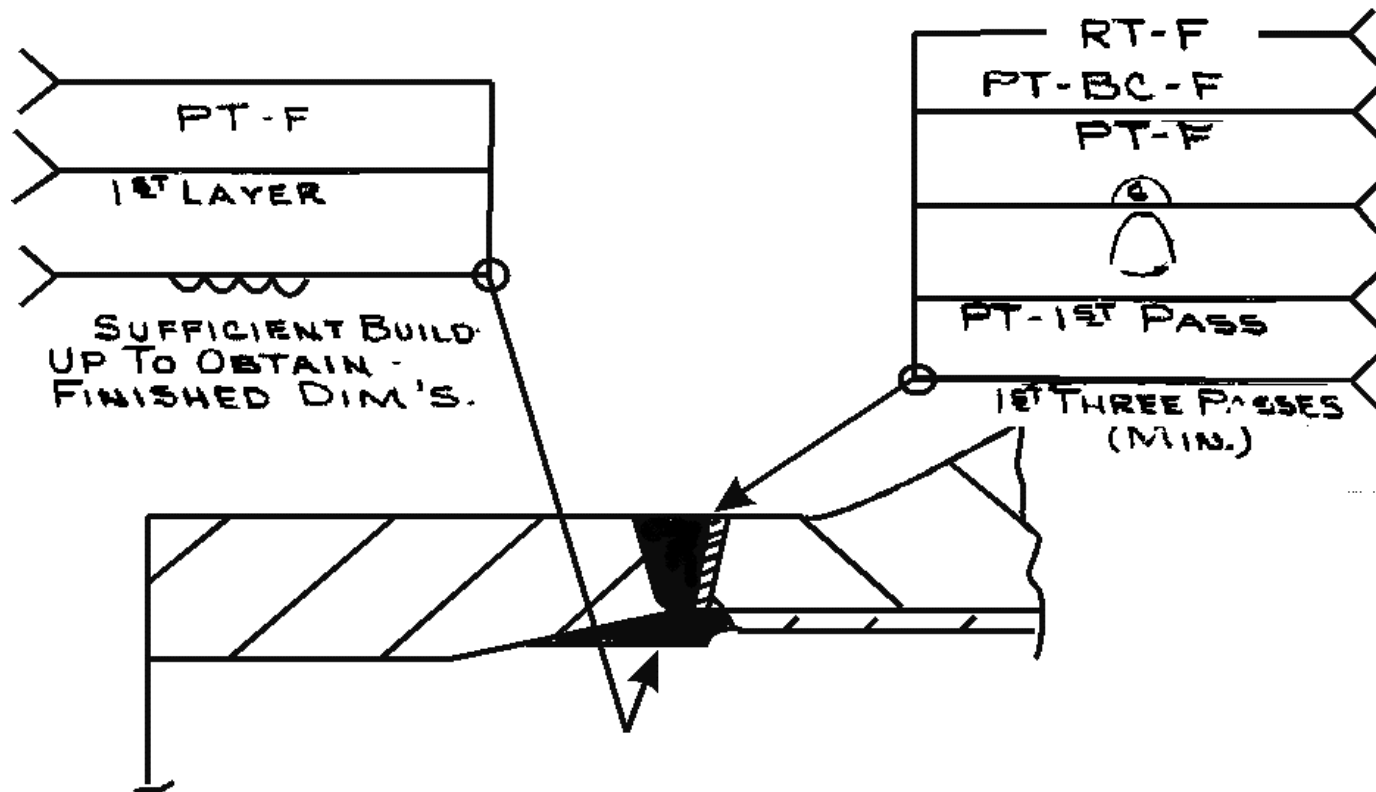
Welding Process for Pressurizer Nozzles

- All welds are U-groove design; land is 0.060 thick minimum
- Weld preps on buttering and safe end are abutted, and clamped in place
- Three initial passes are made: TIG
- PT of the initial pass
- Remainder of weld is completed, OD welding, MIG

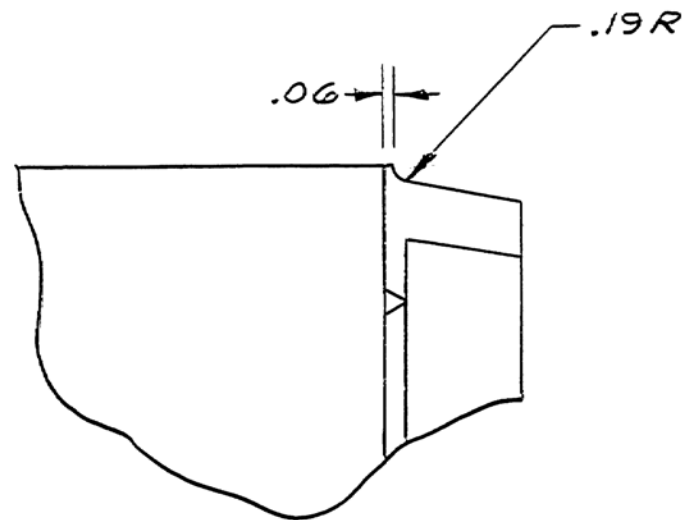
Welding Process for Pressurizer Nozzles (cont'd.)

- Weld ID is ground until any boundary between the two sides disappears (max. depth ~0.7 inches)
- PT applied to verify sound weld
- ID is then re-welded, then PT of ID and OD
- No further welding performed, unless repairs are required as a result of RT
- ID welding is small compared to the overall thickness
- Finite element modeling reflects this process

Westinghouse Design: Weld Detail (Example: Safe End to Surge Nozzle)

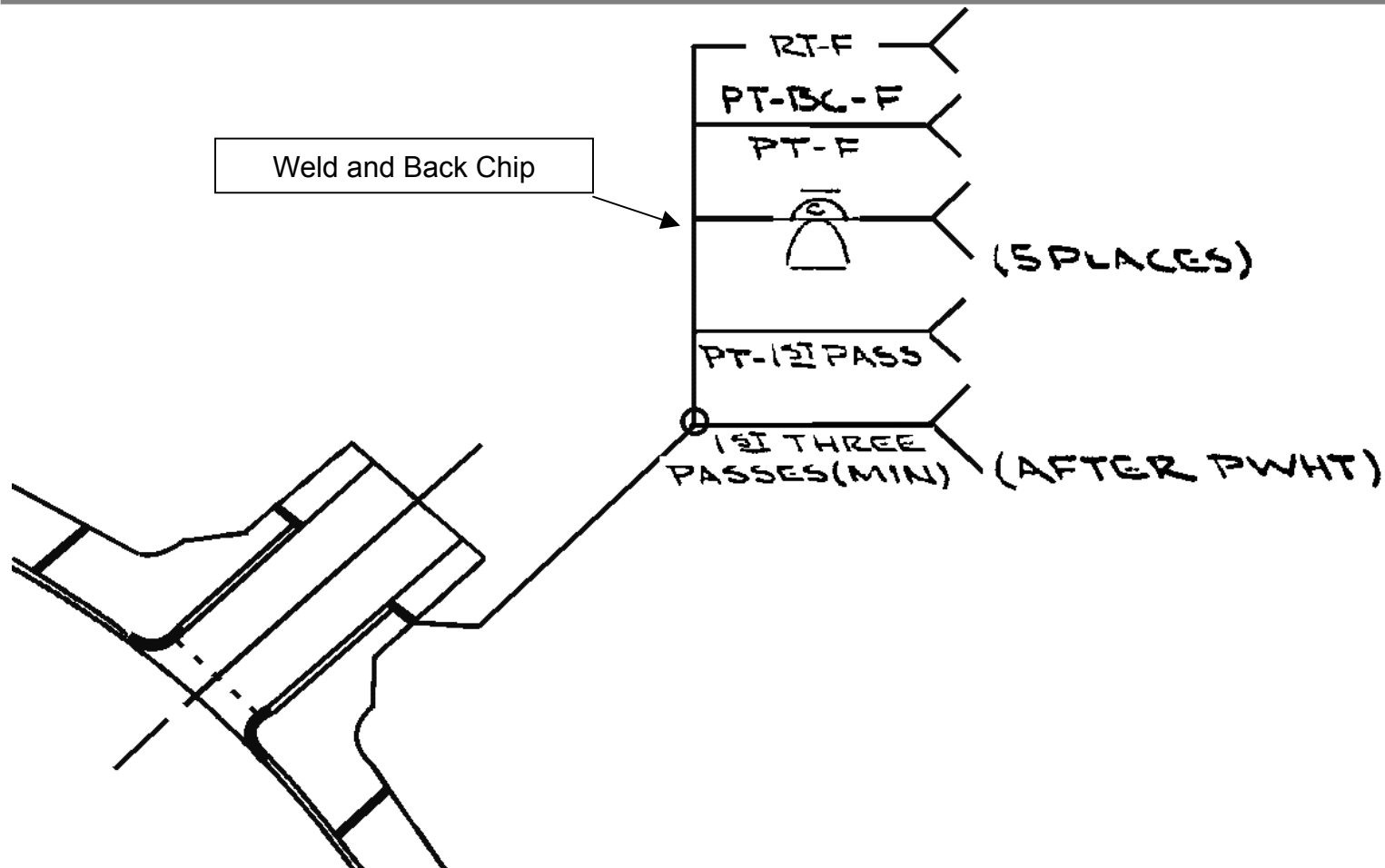


Westinghouse Design: Nozzle Buttering Detail (Surge Nozzle Example)

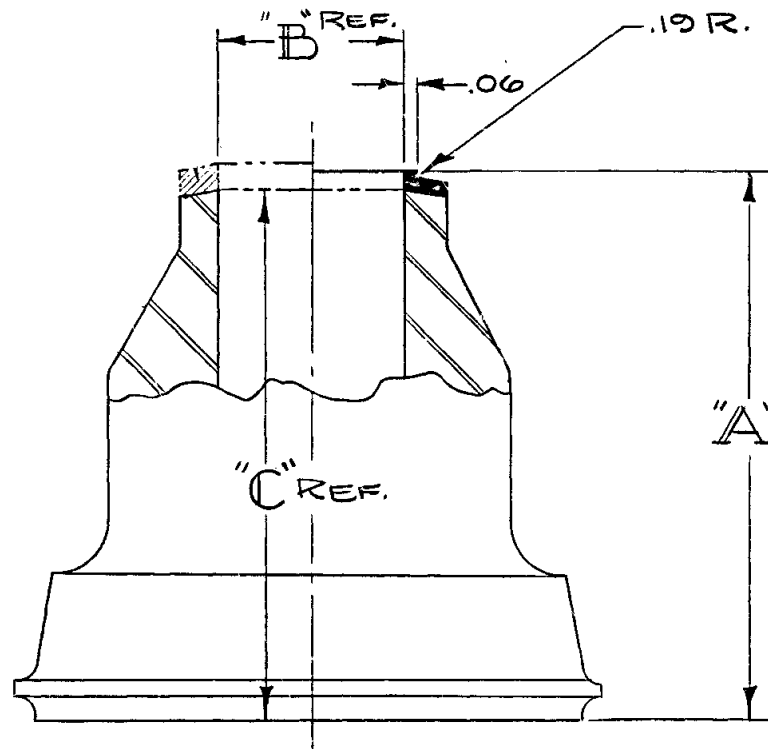


DETAIL A

Westinghouse Design: Weld Detail (Example: Upper Head Safe End to Nozzle)



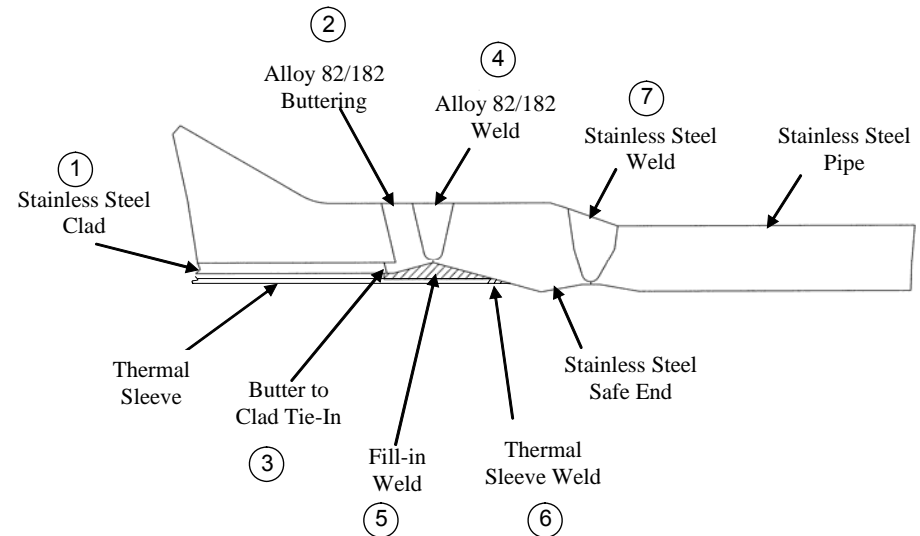
Westinghouse Design: Buttering Detail (Example: Upper Head Nozzle)



Westinghouse Design: Fabrication Time Line (Example: Surge Nozzle)

Example Surge Nozzle Fabrication Time Line

Weld Order	Weld Area Description	Weld Material	NDE
1	Nozzle Cladding	Stainless Steel	PT (All Nozzle Clad)
2	Nozzle Buttering	Alloy 82	PT (B/PWHT) RT (B/PWHT and A/PWHT)
3	Buttering to Cladding Tie-in	Alloy 182	PT surface prior to Weld PT- After Weld
4	Safe-End to Nozzle	1 st 3 passes – Alloy 82 Fill in – Alloy 182 (Included Back Chip)	PT and RT
5	Thermal Sleeve Fill-in Weld	Alloy 82	PT
6	Thermal Sleeve to Safe-End	Alloy 82	PT
7	Pipe to Safe End	Field Weld	



Combustion Engineering Pressurizer

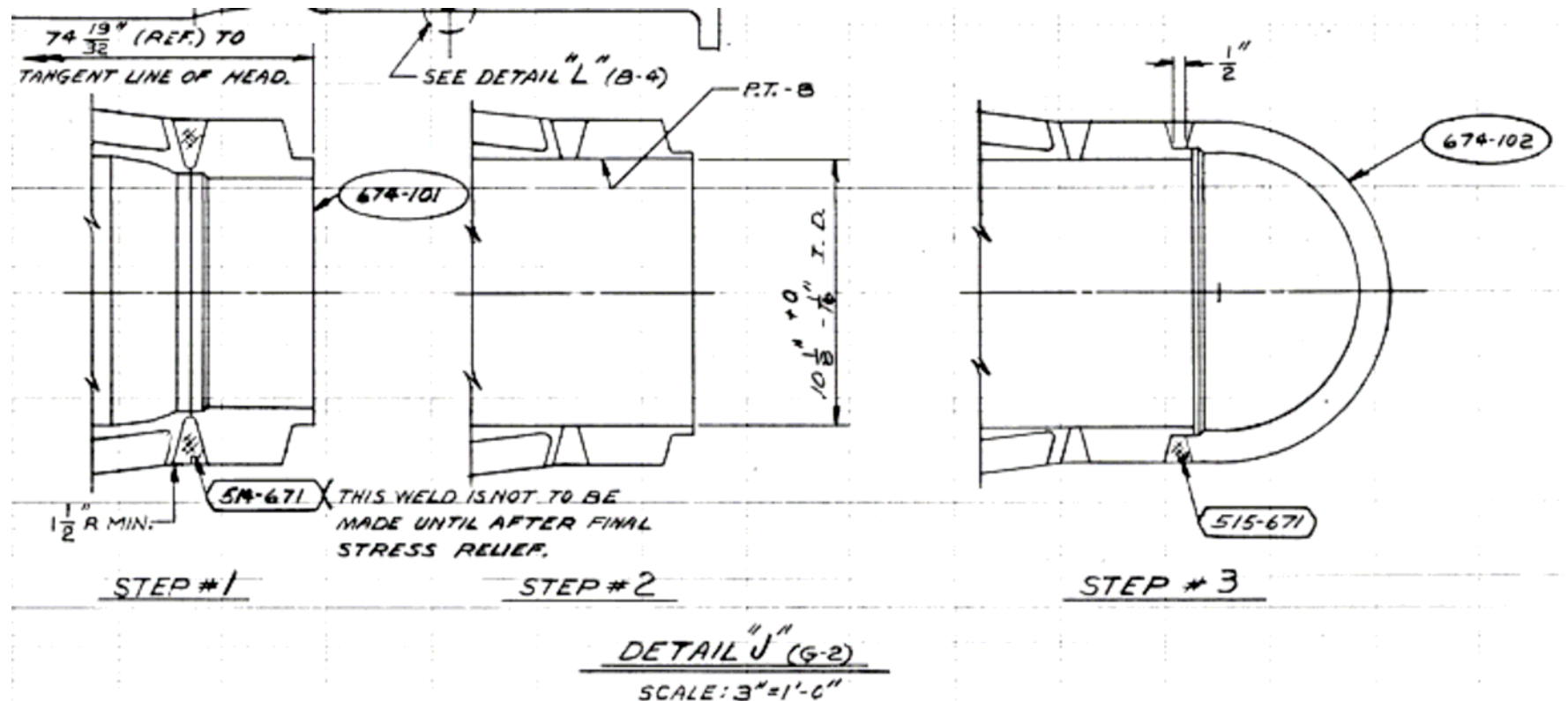
Welding Process for CE Pressurizer Nozzles

- All welds are U-groove design; land is 0.090 thick minimum
- Weld preps on buttering and safe end are abutted, and clamped in place
- Welding process similar to the W process, but ID is purposely undersized on the diameter

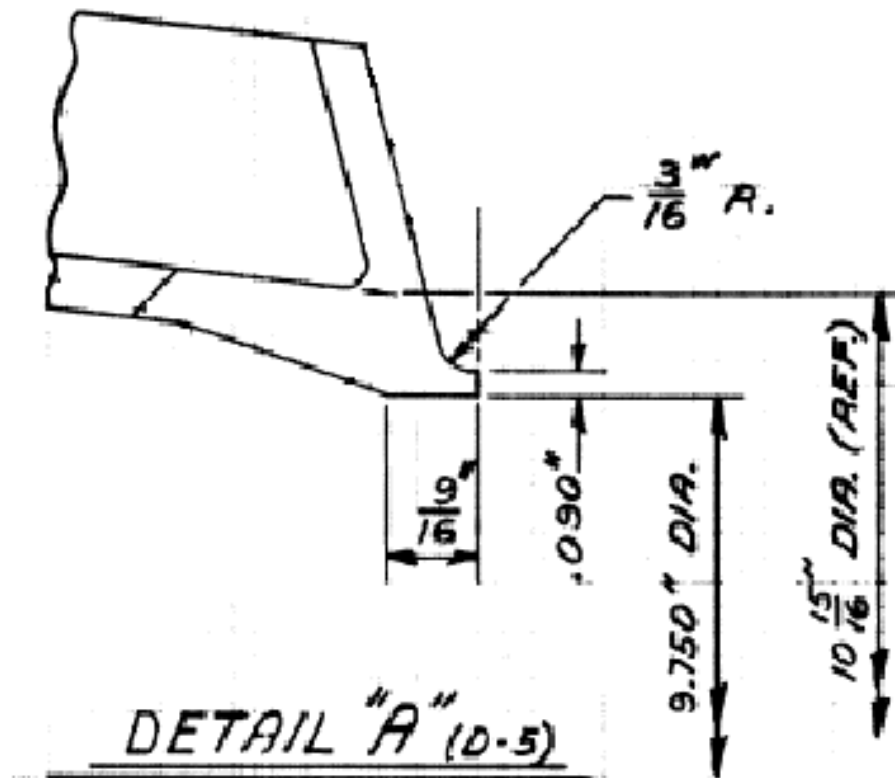
Welding Process for Pressurizer Nozzles (cont'd.)

- Pipe ID is machined to the proper diameter, thus cleaning up the root pass of the weld
- PT of ID applied to verify sound weld
- PT of OD, and RT performed
- No further welding performed, unless repairs are required
- No ID welding

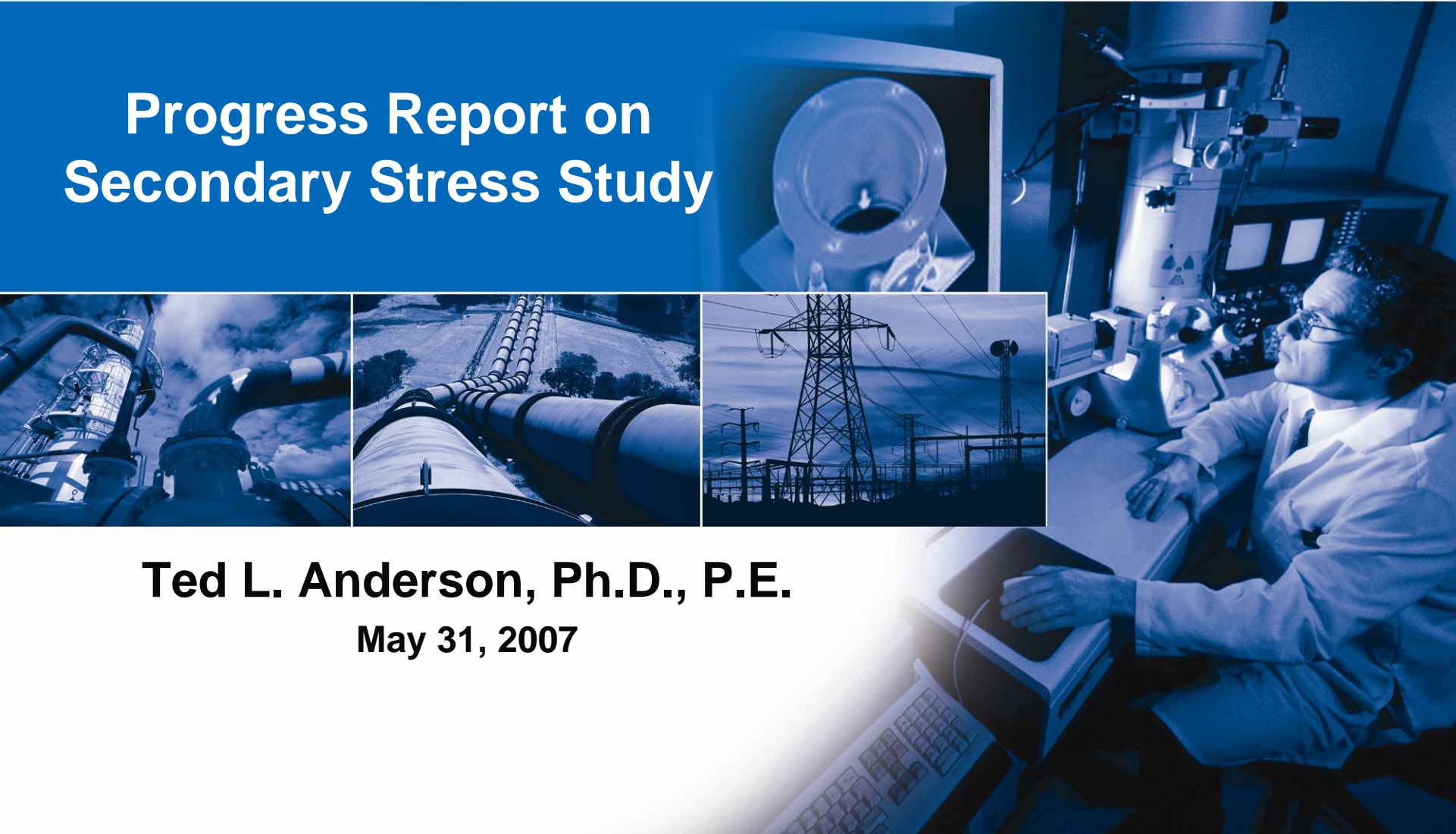
Machining Requirements for CE Designs (Surge Nozzle Example)



CE Design: Nozzle Buttering Detail (Example: Surge Nozzle)



Progress Report on Secondary Stress Study



Ted L. Anderson, Ph.D., P.E.

May 31, 2007

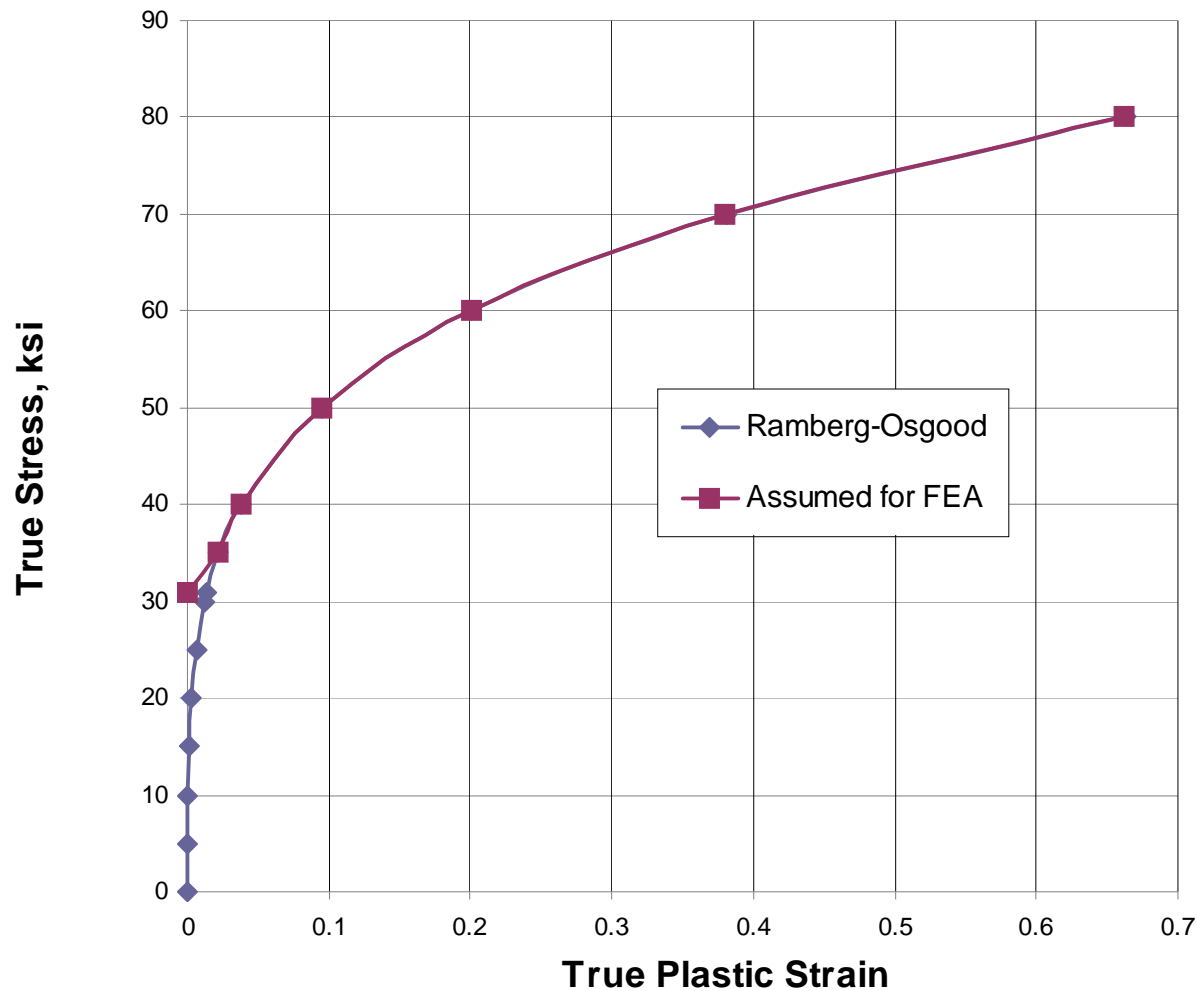
Overview



- ▶ Elastic and elastic-plastic finite element analysis to determine the effect of an imposed end rotation on bending moment and crack driving force.
 - Total pipe length ($2L$) = 60 in & 60 ft (L corresponds to the length of the model due to symmetry conditions).
 - Initial (uncracked) bending stress = 30 ksi (analyses for 10 & 20 ksi currently in progress).
 - Through-wall cracks of various lengths.
- ▶ Moment knock-down factor (M/M_0) for a fixed rotation (θ):
 - Ratio of the bending moment of the cracked pipe to that of the uncracked pipe.

Stress-Strain Curve

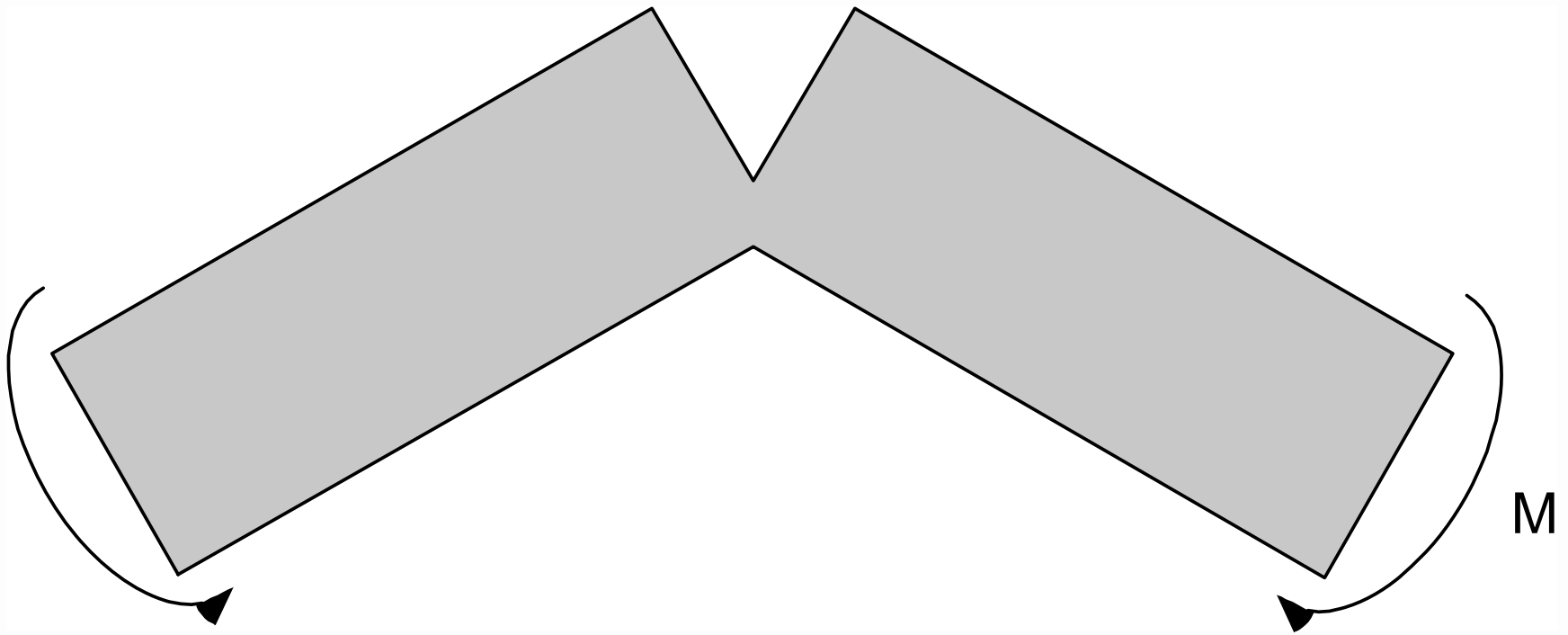
Modified R-O to Avoid Yielding below 30 ksi



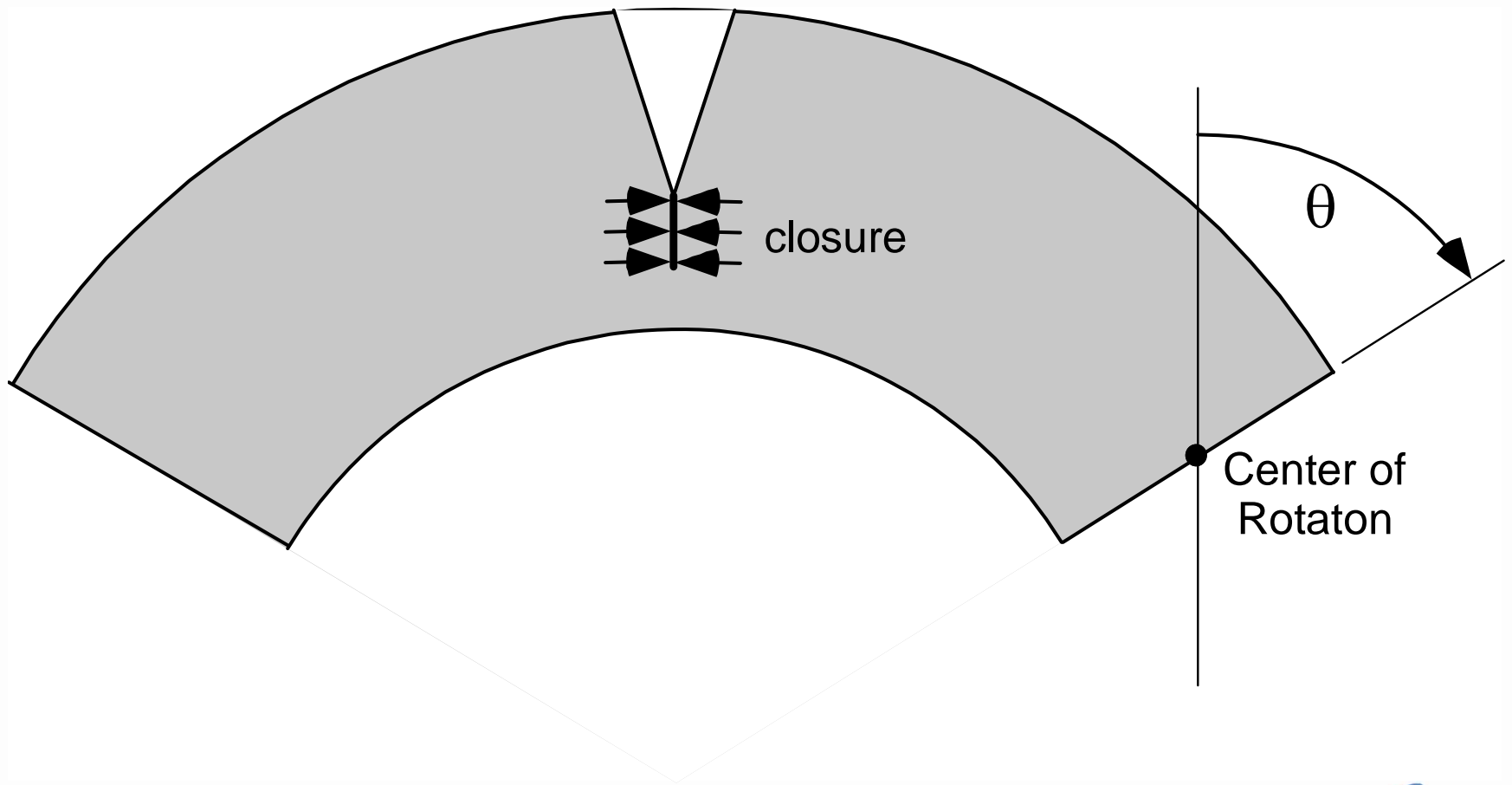
Unexpected Results

- ▶ For an imposed rotation and very long circumferential through-wall cracks, partial closure was observed.
- ▶ Closure was not observed when a moment was imposed.
- ▶ The 3D cracked pipe does not behave according to simple beam theory.

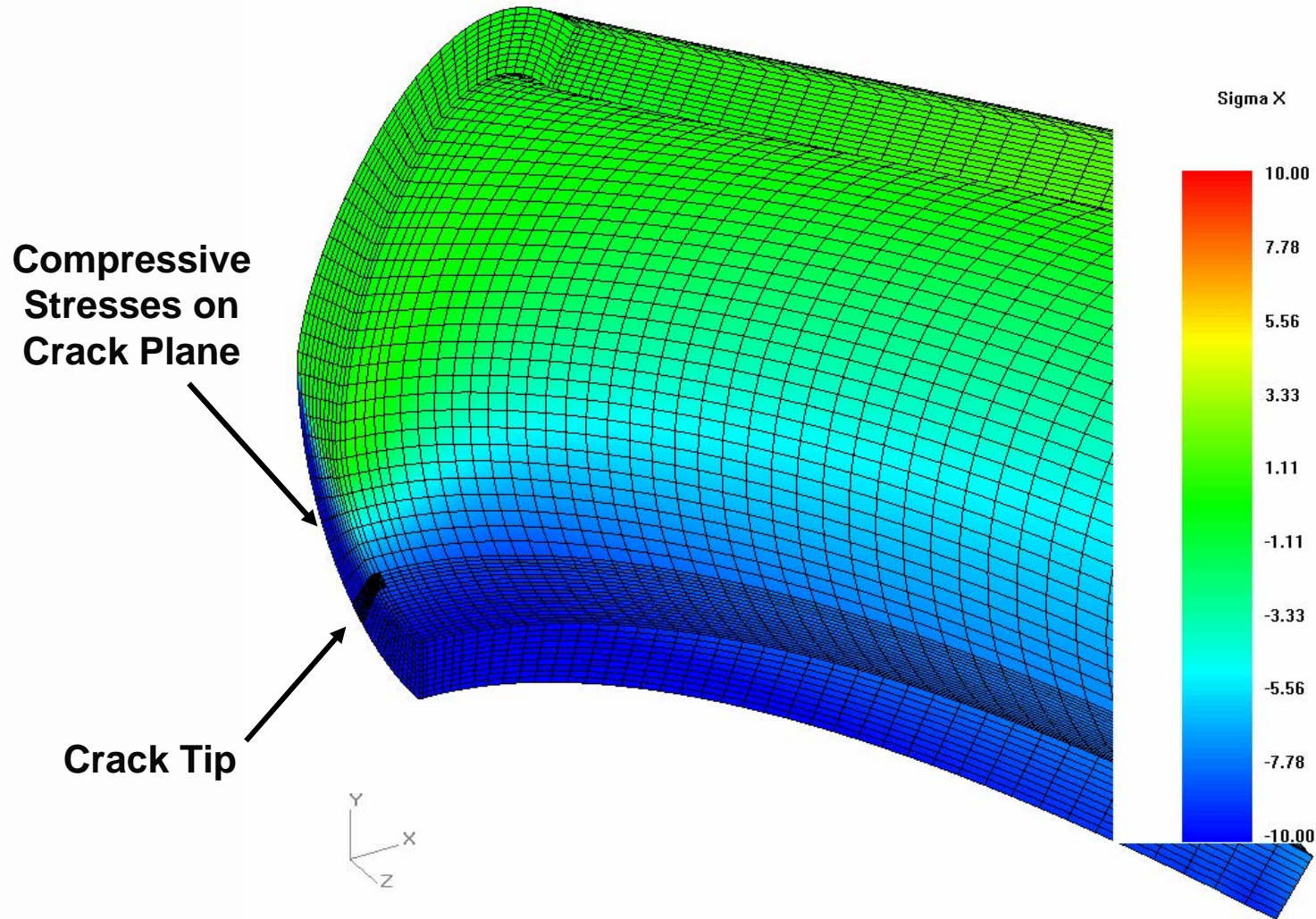
Imposed Moment on Cracked Pipe



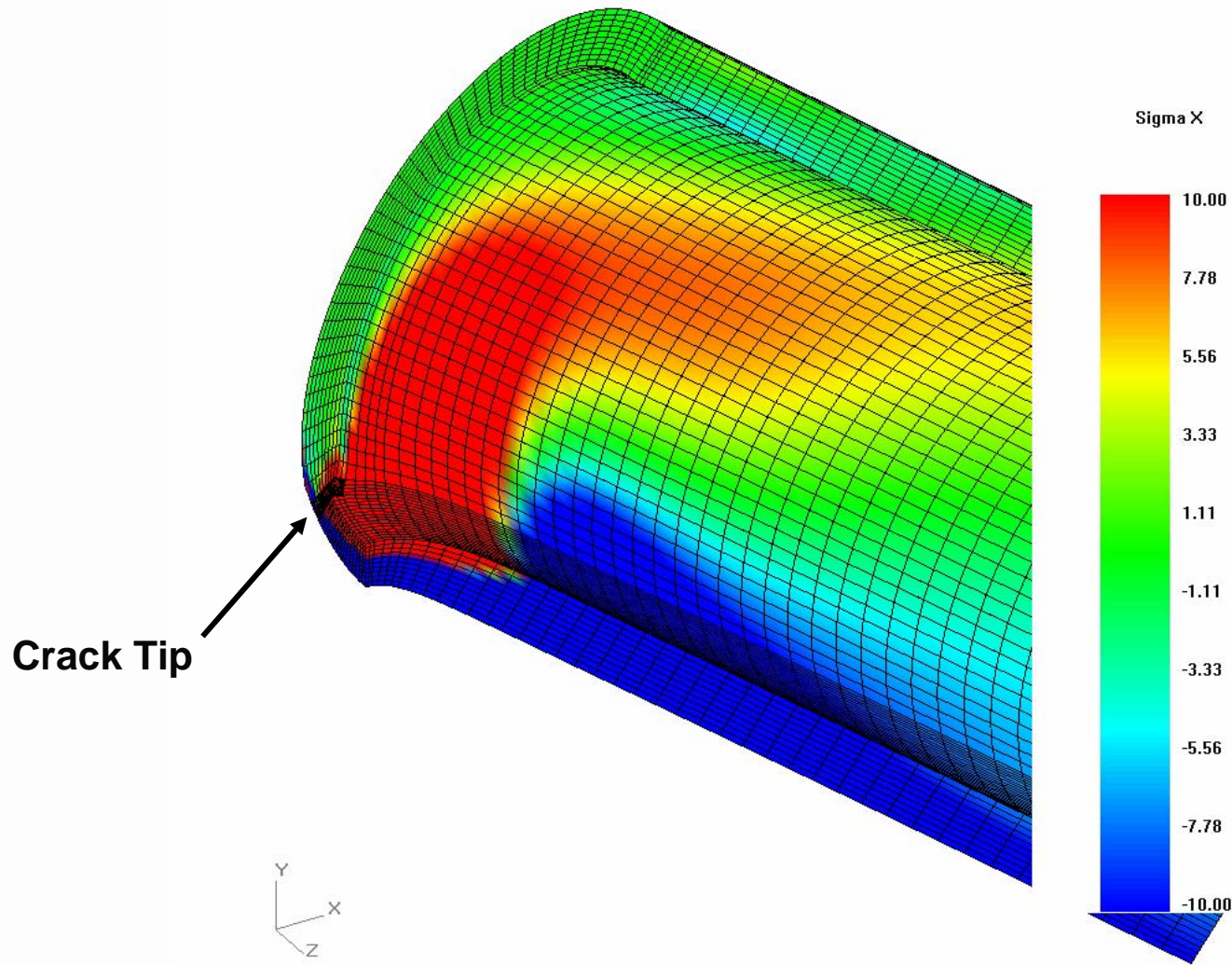
Imposed Rotation on Cracked Pipe



Elastic FEA Results Imposed Rotation



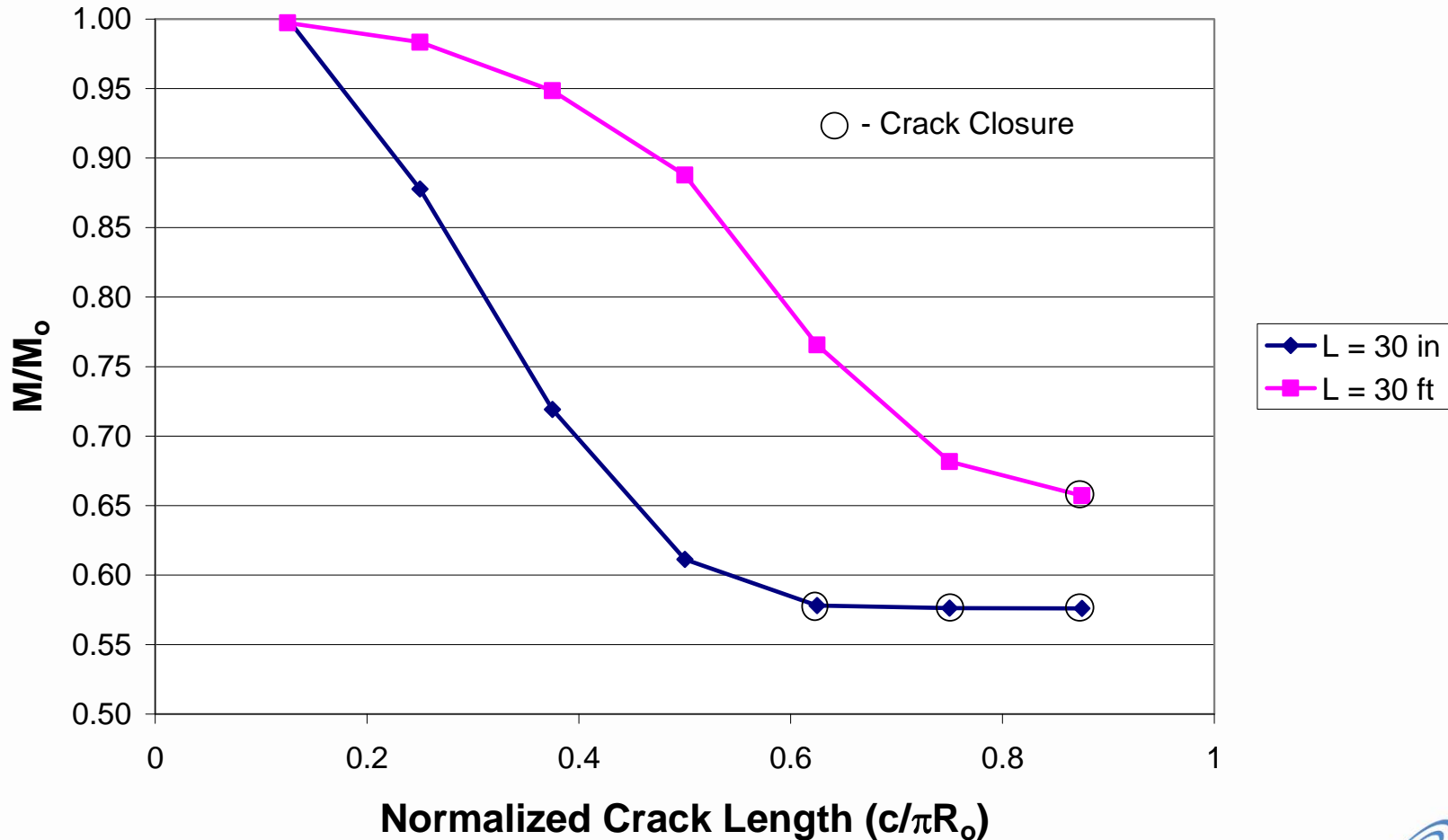
Elastic FEA Results Imposed Moment



Moment Knock-Down Factors

Elastic Analysis

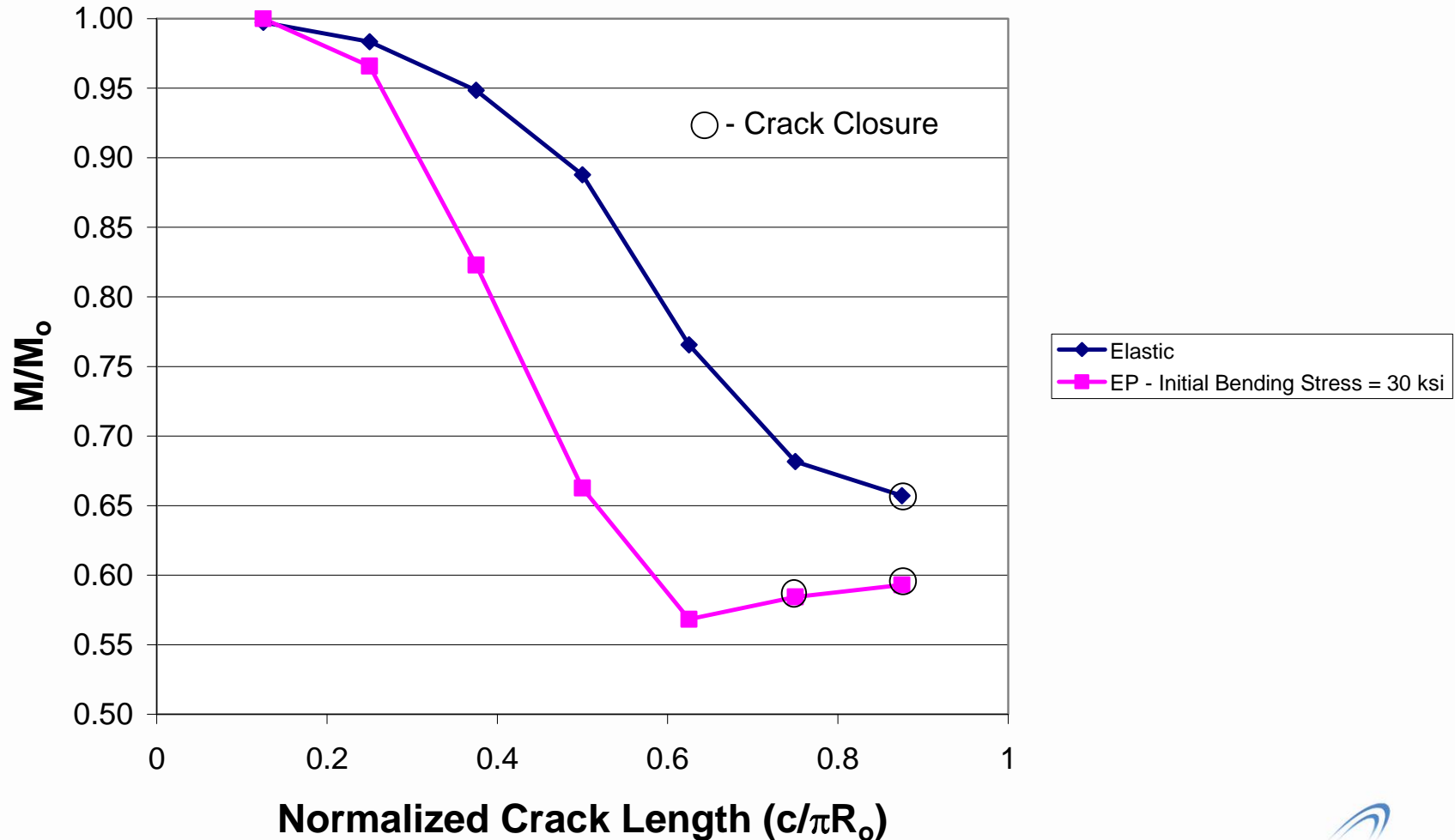
Elastic Analysis, Imposed Rotation



Moment Knock-Down Factors

Elastic & Elastic-Plastic Comparison

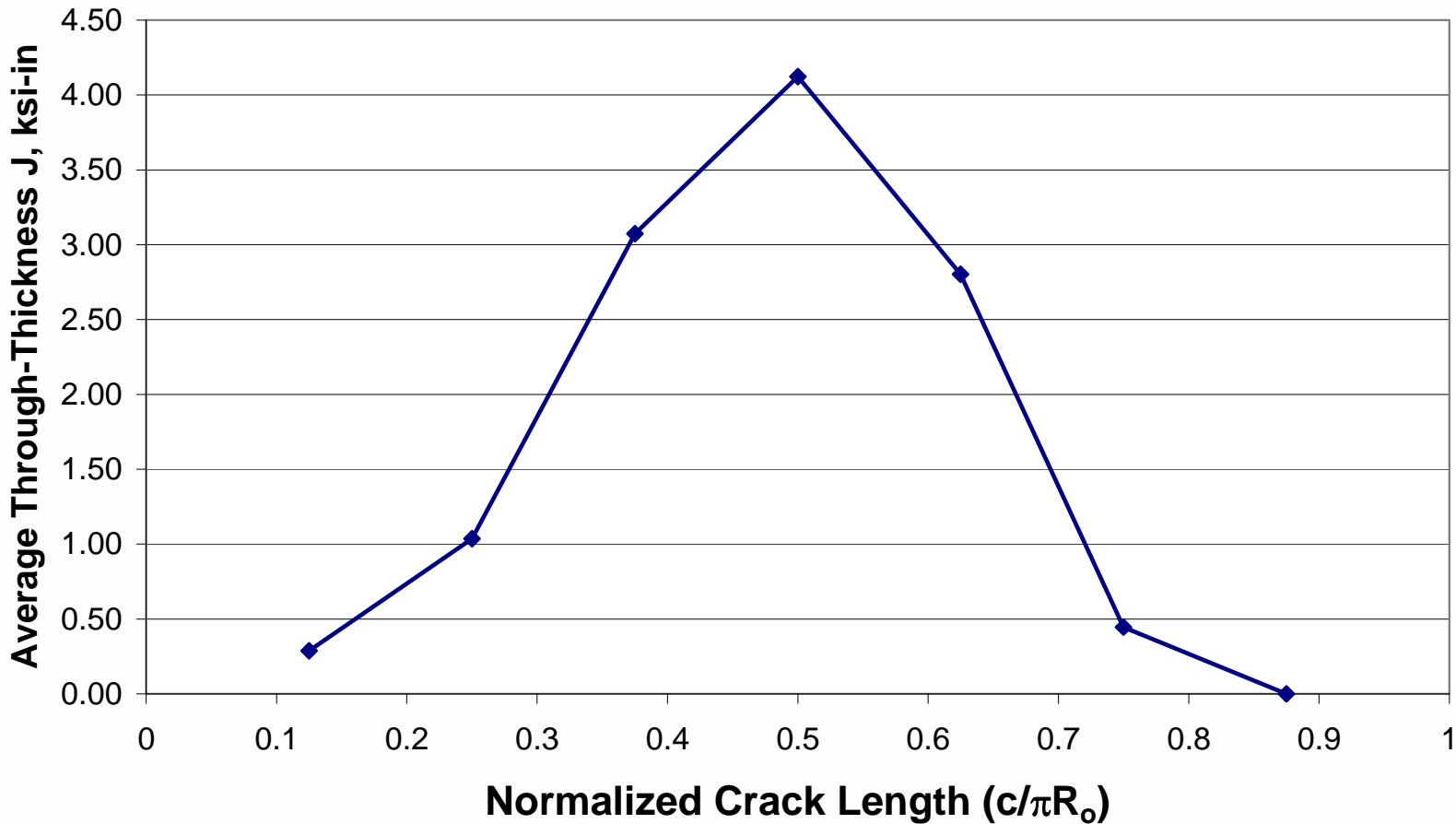
$L = 30$ ft, Imposed Rotation





Elastic-Plastic Crack Driving Force

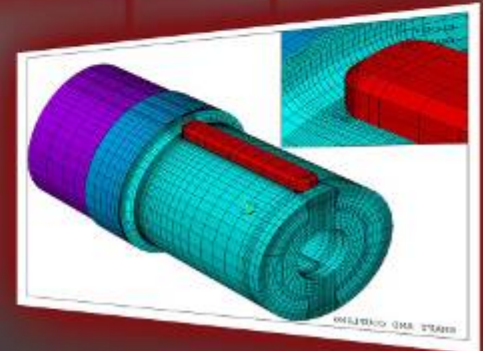
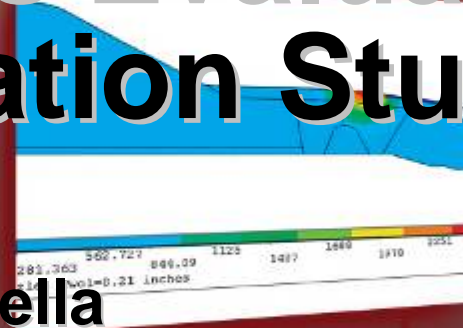
Elastic-Plastic Analysis, $L = 30$ ft
Initial Bending Stress = 30 ksi



Secondary Stress Evaluation Surge Line Rotation Study

Pete Riccardella

May 31, 2007

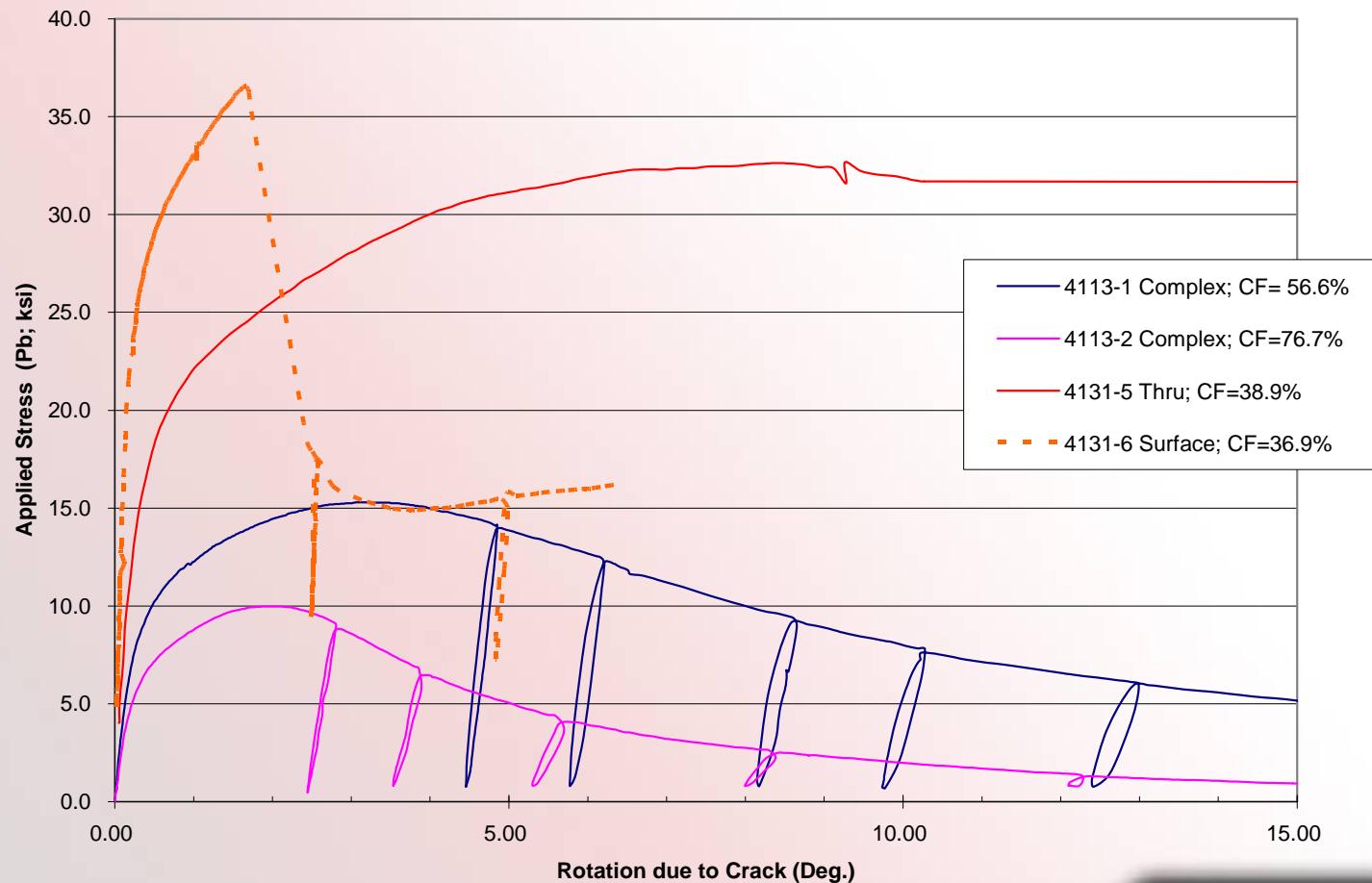


Rotations in Pipe Fracture Experiments

- **Test data reviewed to determine rotations due to presence of crack (at max load and fracture)**
 - Complex cracks vs, thru and surface cracks
 - Complex cracks with various pipe/crack sizes
- **All except surface crack sustained $>2^\circ$ at max load and $>5^\circ$ at fracture**
- **Surface crack sustained 1.7° rotation, but max load corresponded to ligament rupture, not fracture**

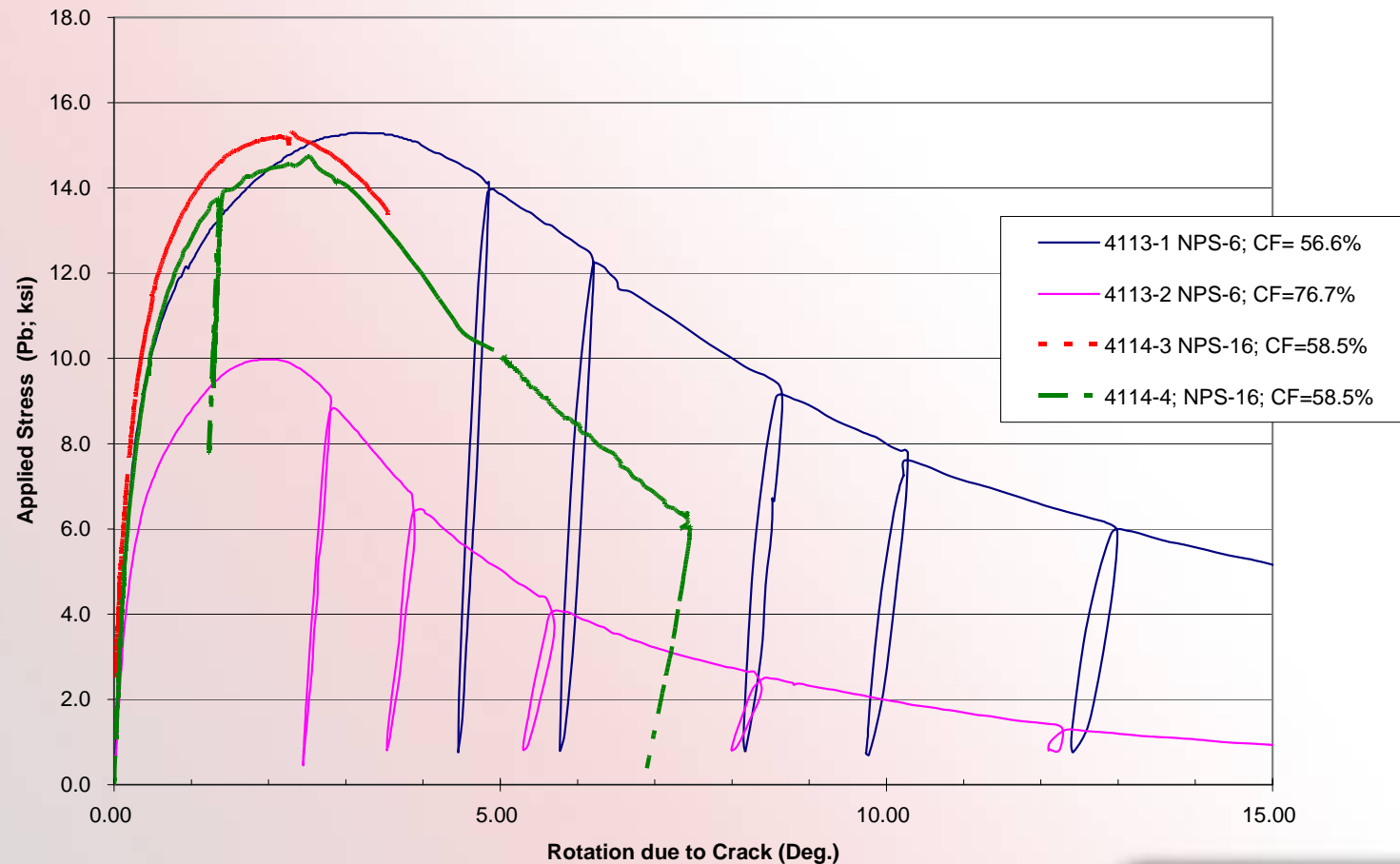
Rotation Due to Crack – Complex vs. Thru and Surface Cracks

Crack Rotation Comparison
(All Pipes 6" NPS; Different Crack Types)



Rotation Due to Crack – Complex Cracks w/ Different Pipe/Crack Sizes

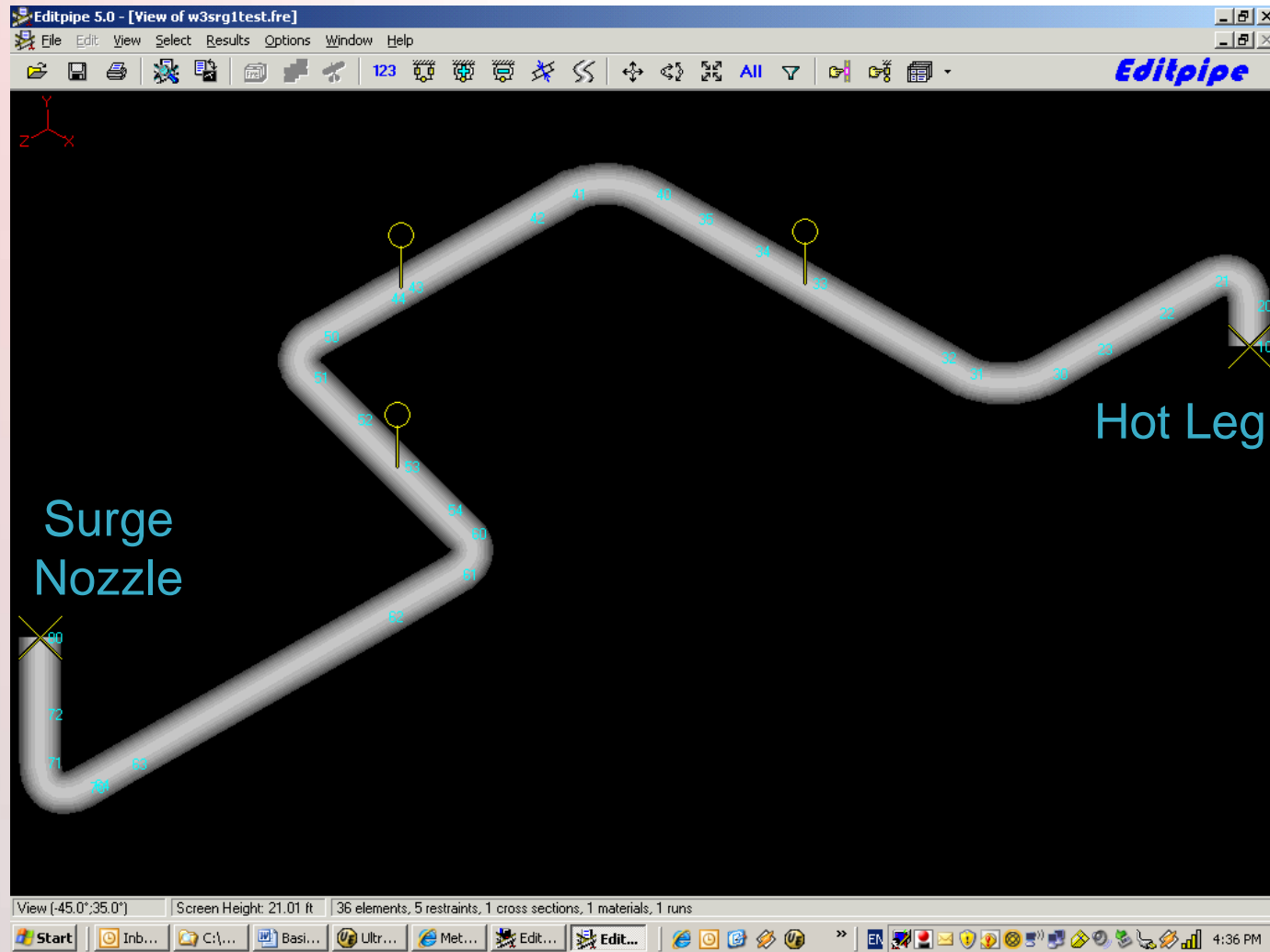
Crack Rotation Comparison
(All Complex Cracks; Different Pipe Sizes)



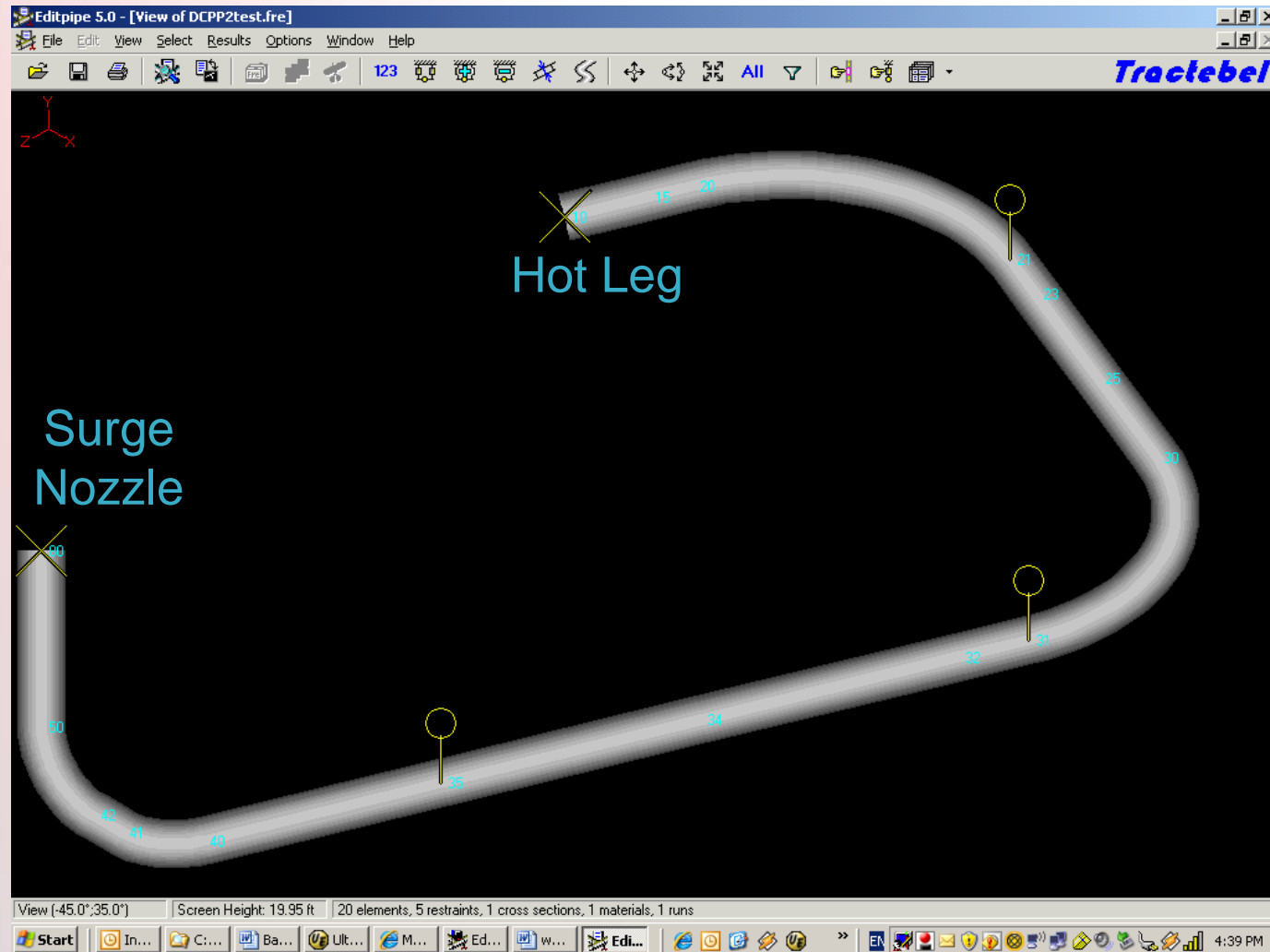
Surge Line Piping Models

- **Surge Line Piping Models developed for one CE and one Westinghouse plant in Group of Nine**
- **Models run with Thermal Expansion, Anchor Movements and Max Thermal Stratification Loads. Bending stresses at surge nozzle:**
 - 19.5 ksi in CE Plant
 - 25 ksi in Westinghouse Plant
- **Rotational Degrees of Freedom at surge nozzle node then released under same loading conditions to determine max rotation at surge nozzle that these loads could produce**

CE Plant Surge Line Piping Model



W Plant Surge Line Piping Model



Nodal Release Results

	Summary of Results - Pressurizer Surge Nozzle Moment vs. Rotation								
	Fixed-Fixed Bending Moments				Fixed-Pinned Rotations (Deg.)				Notes
	Mx, ft-kip	My	Mz	Stress, ksi	Rx, deg.	Ry	Rz	SRSS	
CE Plant	176.303	43.701	5.771	19.485	1.38	0.66	0.97	1.81	1, 2, 3
Westinghouse Plant	138.881	103.841	3.809	24.854	1.13	1.08	0.84	1.77	1, 2, 4
Notes:									
1. My is torsion direction.									
2. Loads include thermal expansion, anchor movement, and stratification									
3. Stratification delta T is 320 F.									
4. Stratification delta T is 270 F.									

Conclusions

- **Large Complex Cracks can sustain $>2^\circ$ rotation at crack**
 - even greater if additional flaw tolerance, beyond max load is credited
- **Maximum rotation that could be produced at surge nozzle for two representative surge lines, under worst case secondary loads (thermal + stratification) is $<2^\circ$**
- **Therefore, these loads would be completely relieved prior to fracture**

Implication of Wolf Creek Indications

Verification and Confirmatory Analyses

***David Rudland, Heqin Xu, Do-Jun Shim, and Gery Wilkowski
Engineering Mechanics Corporation of Columbus***

May 31, 2007



Innovative Structural Integrity Solutions

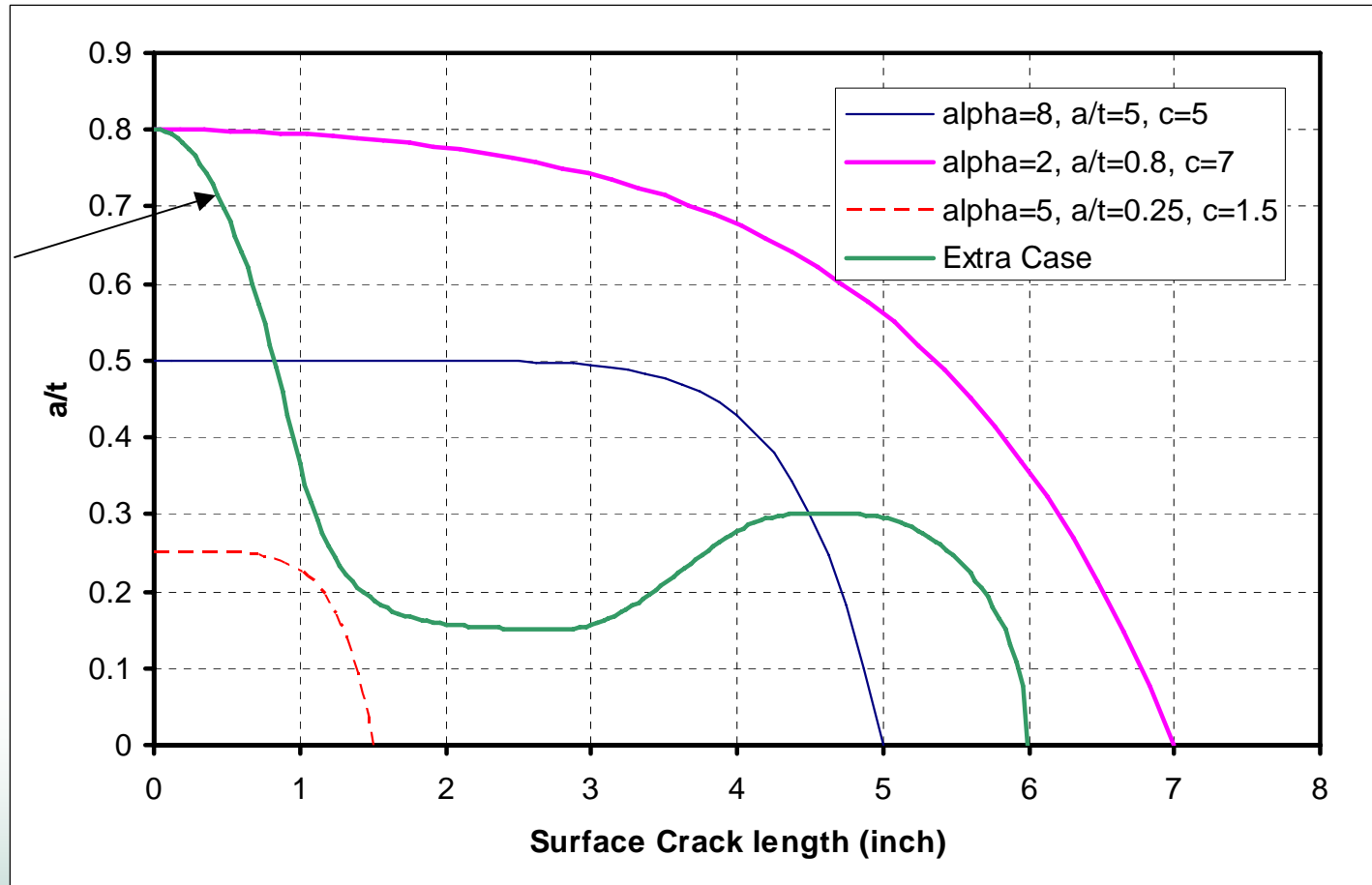
Outline

- *K Verification*
- *Critical Crack Size*
- *Welding Residual Stress*
- *Convergence study – and other Relief Nozzle Calculations*
- *Leakage calculations*
- *Plans*

Continuous Arbitrary Surface Cracks

Modified Bessel of the first kind

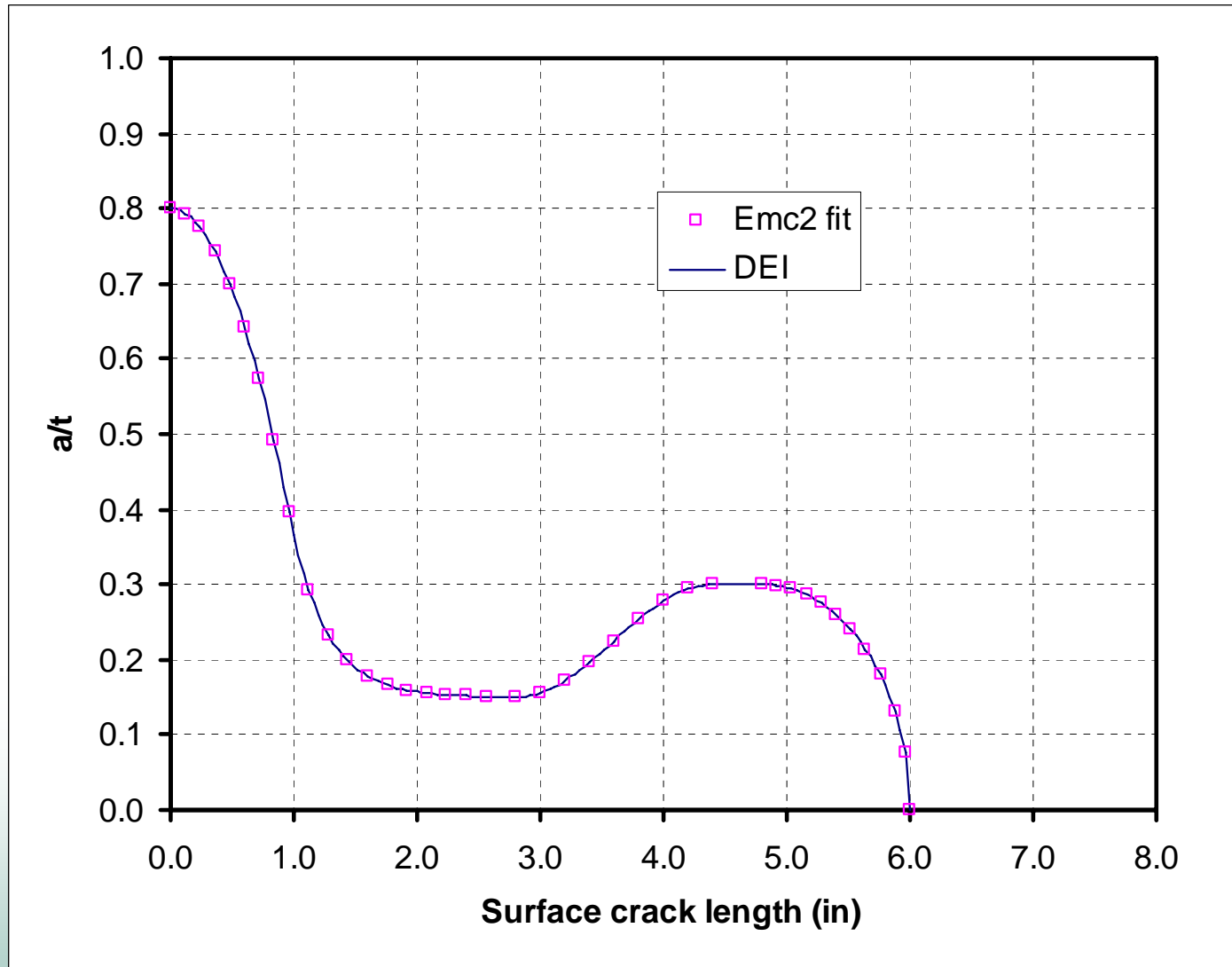
**Developed
by DEI**



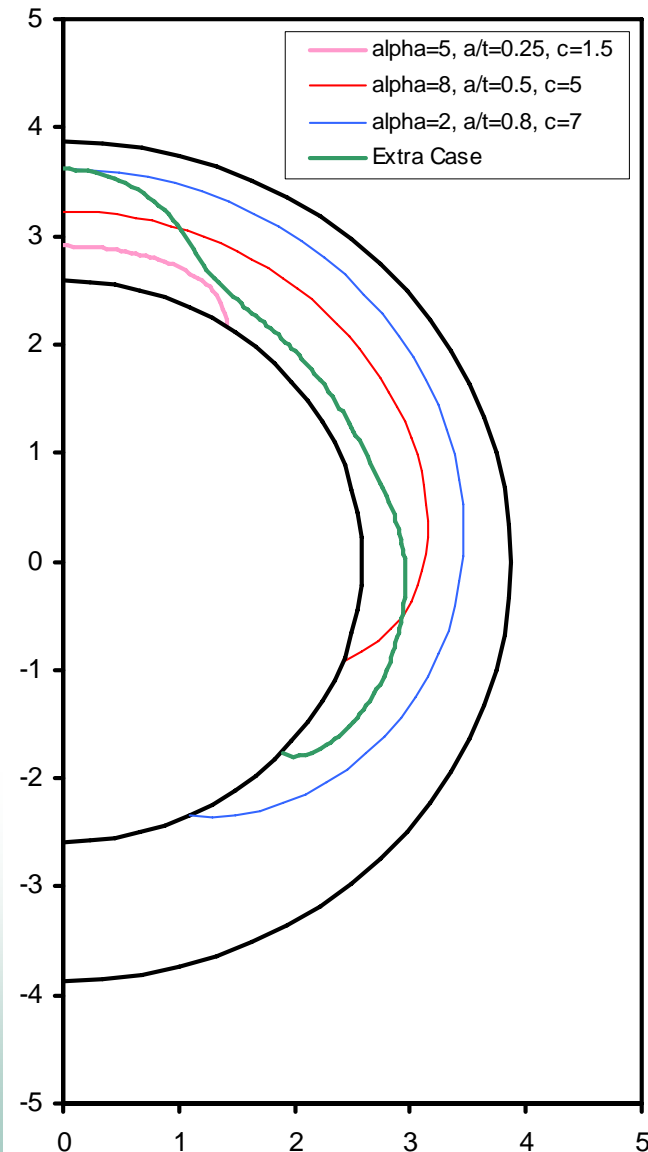
$$I_{\alpha}(x) = i^{-\alpha} J_{\alpha}(ix) \quad J_{\alpha}(x) = \frac{1}{2\pi} \int_0^{2\pi} \cos(\alpha\tau - x \sin \tau) d\tau \quad \mathfrak{E}^{mc^2}$$

Innovative Structural Integrity Solutions

Continuous Arbitrary Surface Crack

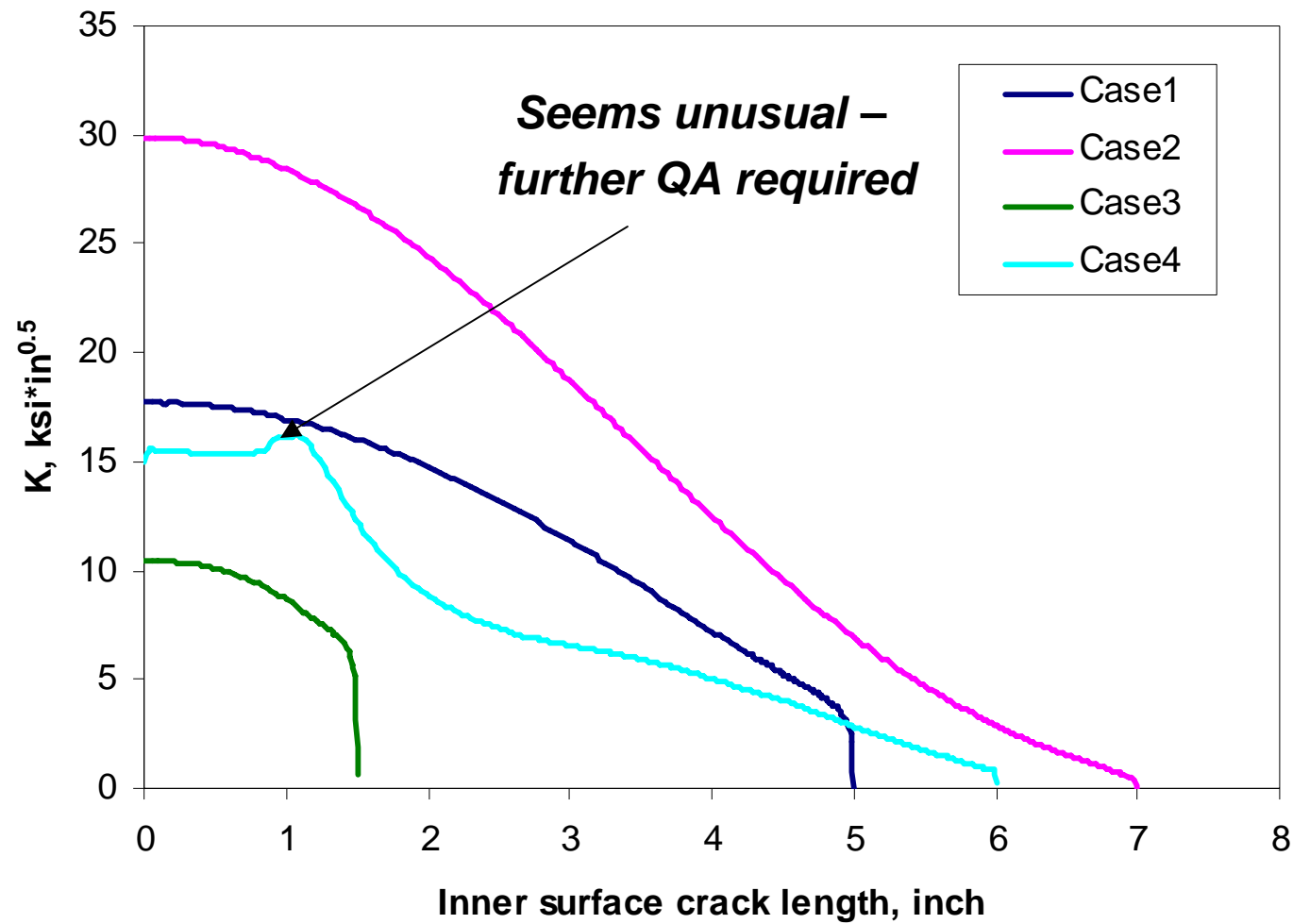


Continuous Arbitrary Surface Cracks



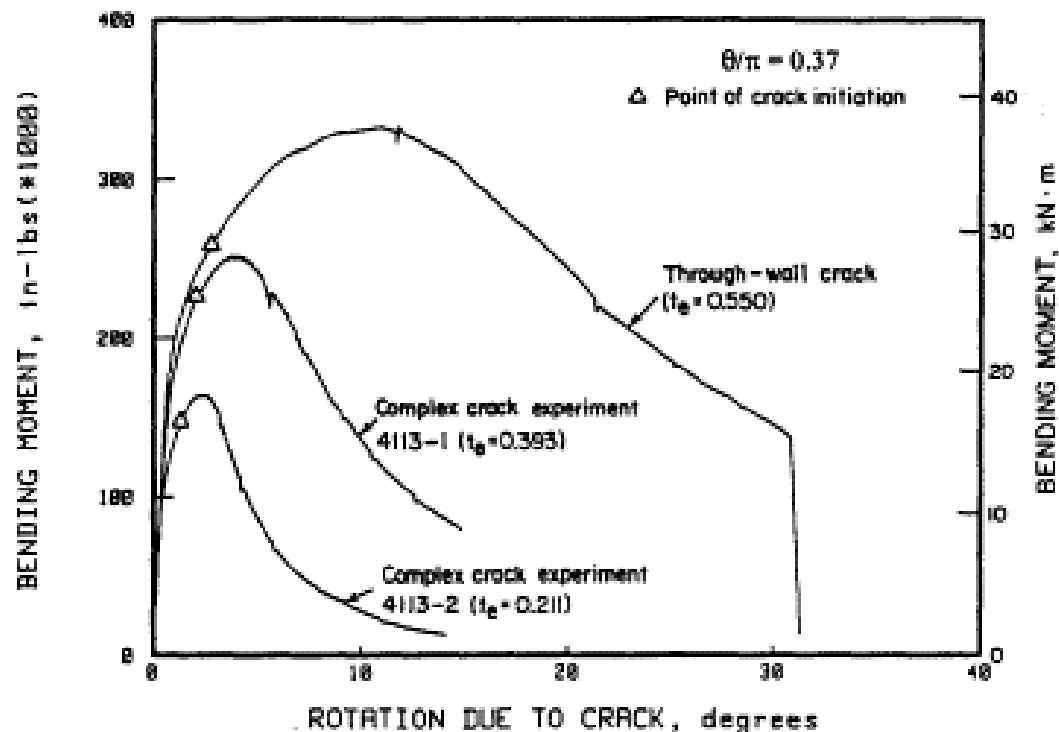
- **Applied loads – Tension and Bending only – No WRS**
- **Used Wolf Creek relief nozzle geometry**
- **Wolf Creek relief nozzle loads – Phase 1**

K-Verification



Degraded Piping Program TP304 Pipe Data

- **Past complex cracked-pipe fracture test observations**
 - ◆ **Lowers maximum loads (due to thickness reduction even for limit-load) and**
 - ◆ **Lowers rotation due to the crack (from toughness reduction due to constraint) even for limit-load failures –**
 - **If reduction high enough, then may become EPFM failure for maximum load**

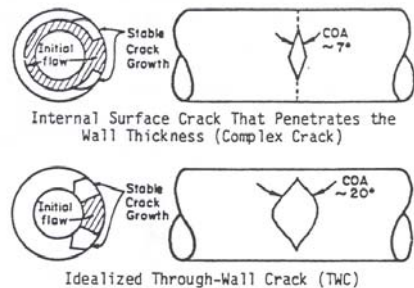


Past Complex-Cracked-Pipe Fracture Test Observations

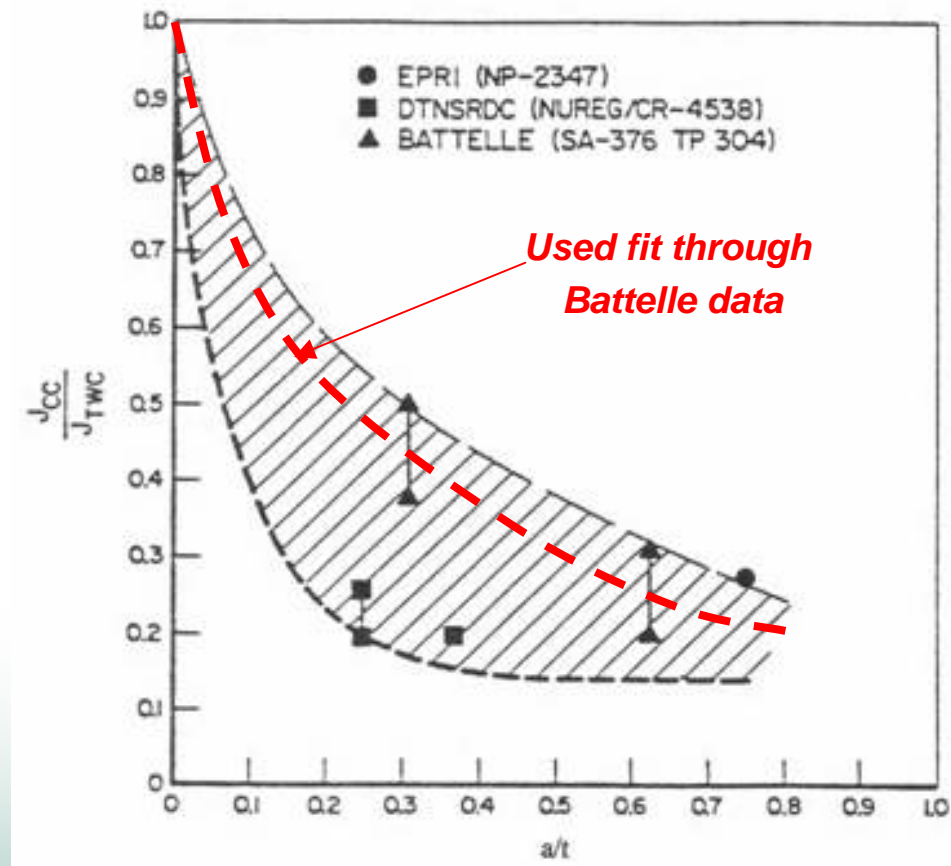
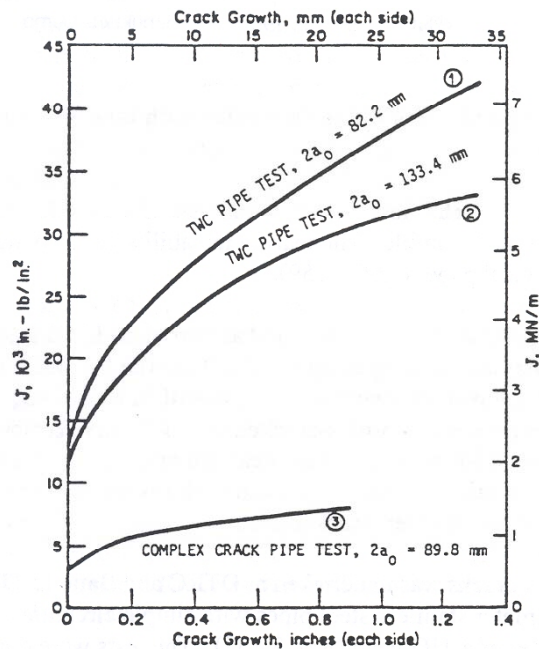
- ***Most tests in past on nominal 6" diameter pipes***
 - ***TP304, Alloy 600, A106B***
 - ***One Alloy 600 pipe test with shim in compressive machined notch region to obtain full compression on crack closure side from start of initial loading***
- ◆ ***Two tests on 16" diameter TP304 pipe***
 - ***Experimentally observed after the test that there was crack closure even in machined notch region on bottom of pipe (NUREG/CR-4082 V7, pg 2-7)***
- ◆ ***Change in calculated J-R curve proportional to measured decrease in CTOA with complex cracks***

Original EPRI Complex-Cracked Pipe Test Results

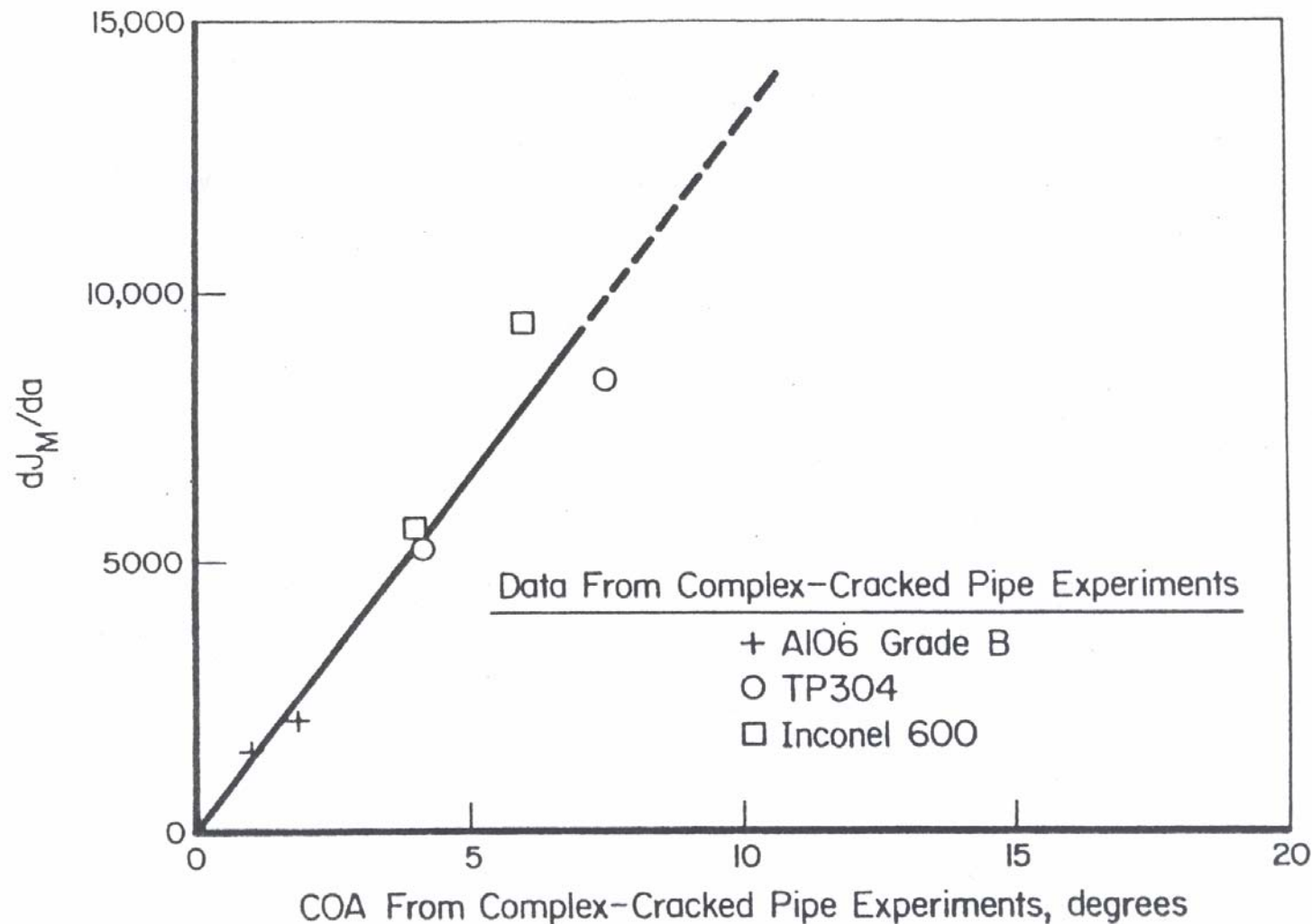
■ Past complex cracked-pipe fracture test observations



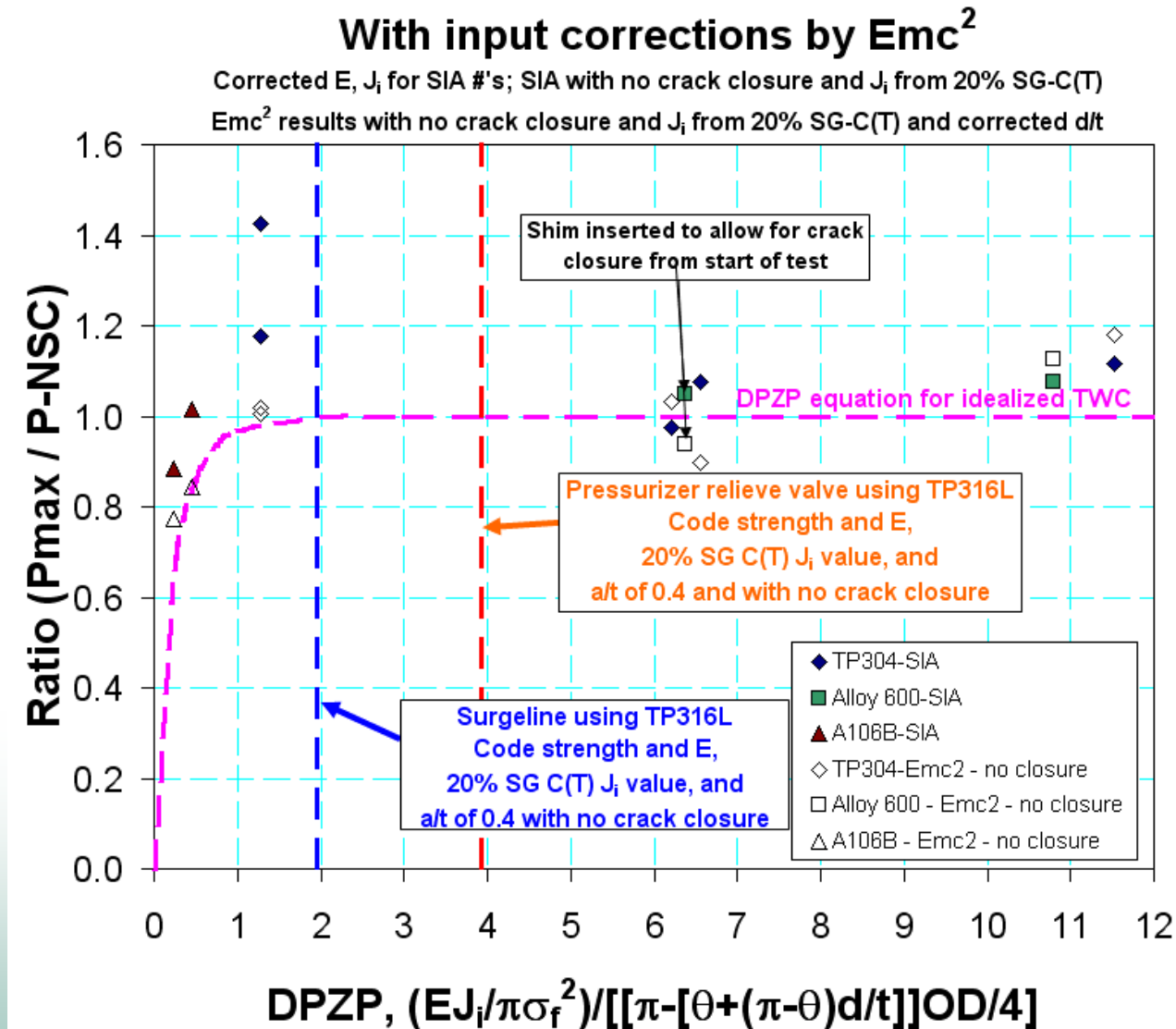
Circumferential crack morphology during ductile tearing



Change in Calculated J-R curve Proportional to Measured Decrease in CTOA with Complex Cracks



Comparison of SIA and Emc² Analysis of Complex-Cracked Pipe Tests – (Assumptions of no crack closure)



Emc²

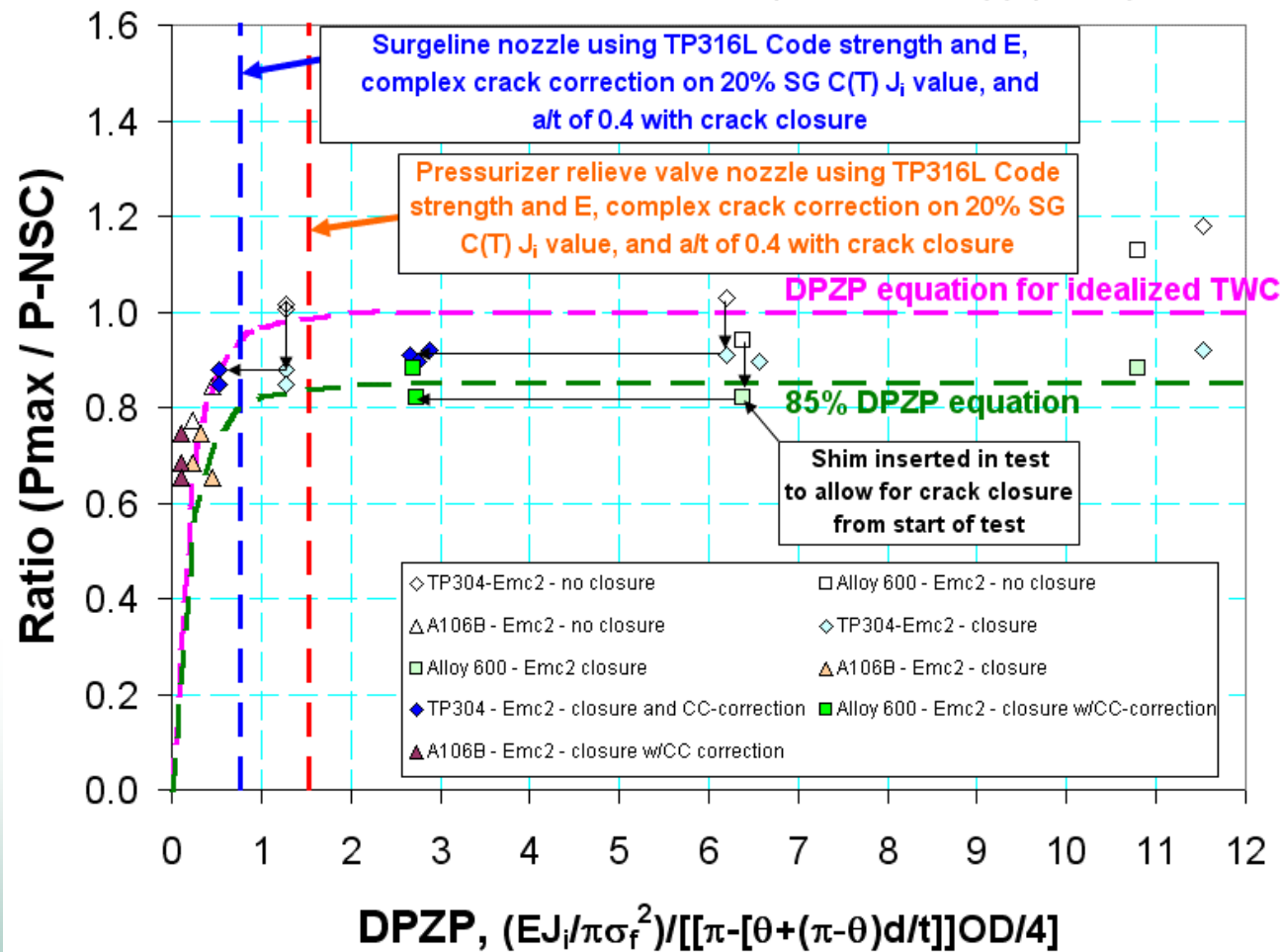
Innovative Structural Integrity Solutions

Emc² Analysis With and Without Crack Closure, and With Complex-Crack Constraint Correction

Emc² Results Only

(Using corrected E, d/t, J_i from 20% SG-CT

CC correction = constraint correction for complex cracks on C(T) J_i values)



Emc²

Innovative Structural Integrity Solutions

Summary for Complex-Cracked Pipe Maximum Moment Predictions

- ***Use one of following options – depending on QA of equations with data to be similar to Emc^2 trends***
 1. ***Use no crack closure for limit-load analysis, with TWC Z-factor, or***
 2. ***Use NSC crack closure with 85% of DPZP equation with complex crack constraint correction on C(T) specimen J_i values (green curve fit previous slide)***
 - ◆ ***Reasonable lower bound to experimental data, so negligible uncertainty***
 - ◆ ***Gives about the same results as 1.) for pressurizer nozzle sizes***

Welding Residual Stress

■ *From May 1st meeting*

◆ *Surge Nozzle*

- *Typical Type 8 geometry with no repairs. Includes the A182 filler weld for the thermal sleeve*
- *Same as Type 8 expect with a 0.5" (or maybe 5/16") deep weld repair – Geometry shows 5/16" from bottom of bevel"*
- *CE nozzle (Type 9). This could be similar to Type 8 except without the filler weld.*
- *One of these cases with the stainless steel safe end weld. Would suggest Type 8.*

Welding Residual Stress

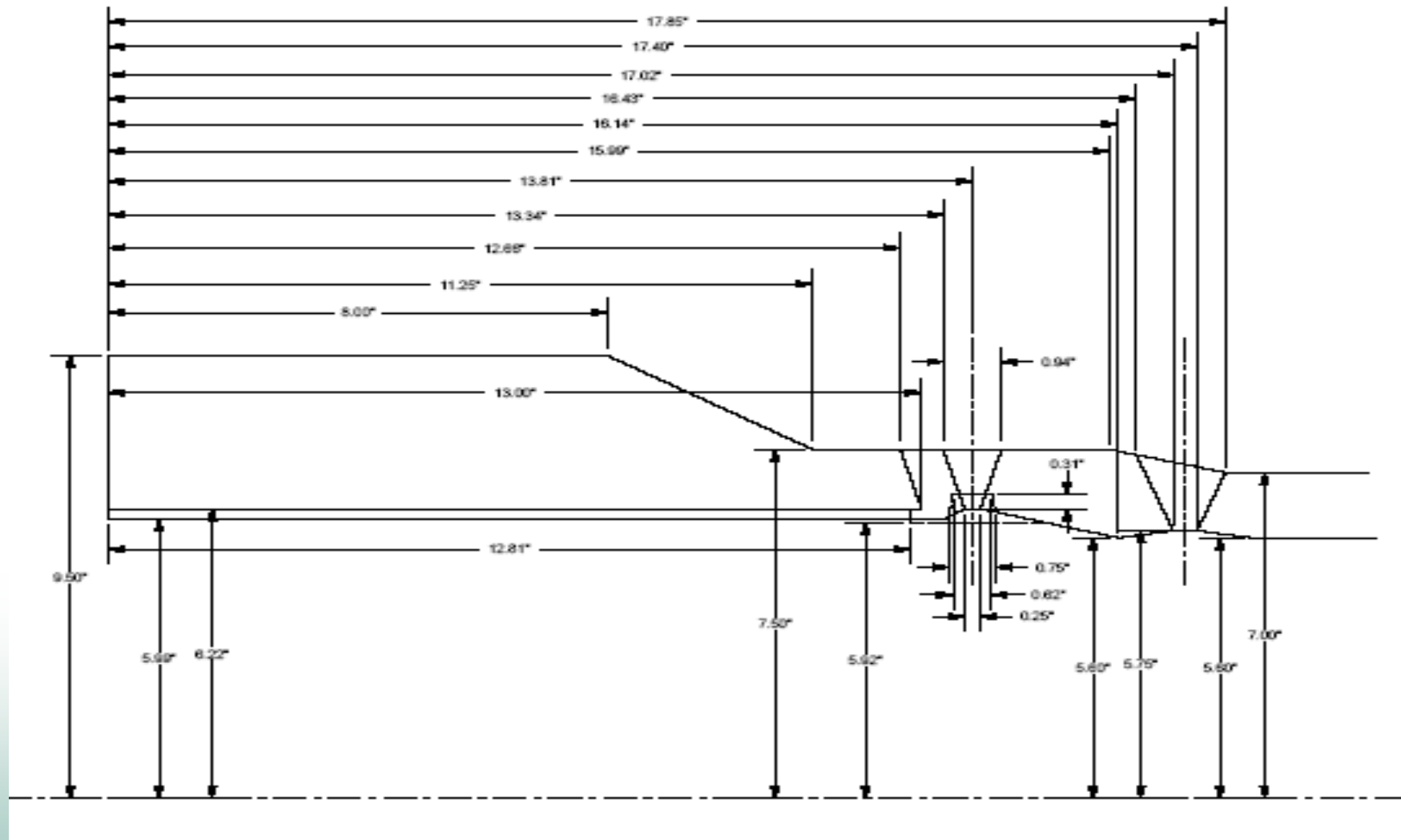
◆ Relief/Safety Nozzle

- *Typical unrepaired geometry without a liner – Type 1a (like Wolf Creek)*
- *Typical unrepaired geometry with liner – Type 2b*
- *Typical geometry without a liner with deep (40-70%) ID repair – Not on DEI list. They plan a repair on liner geometry*
- *Typical geometry without a liner with stainless steel safe end repair*
- *Combination of 3.) and 4.)*

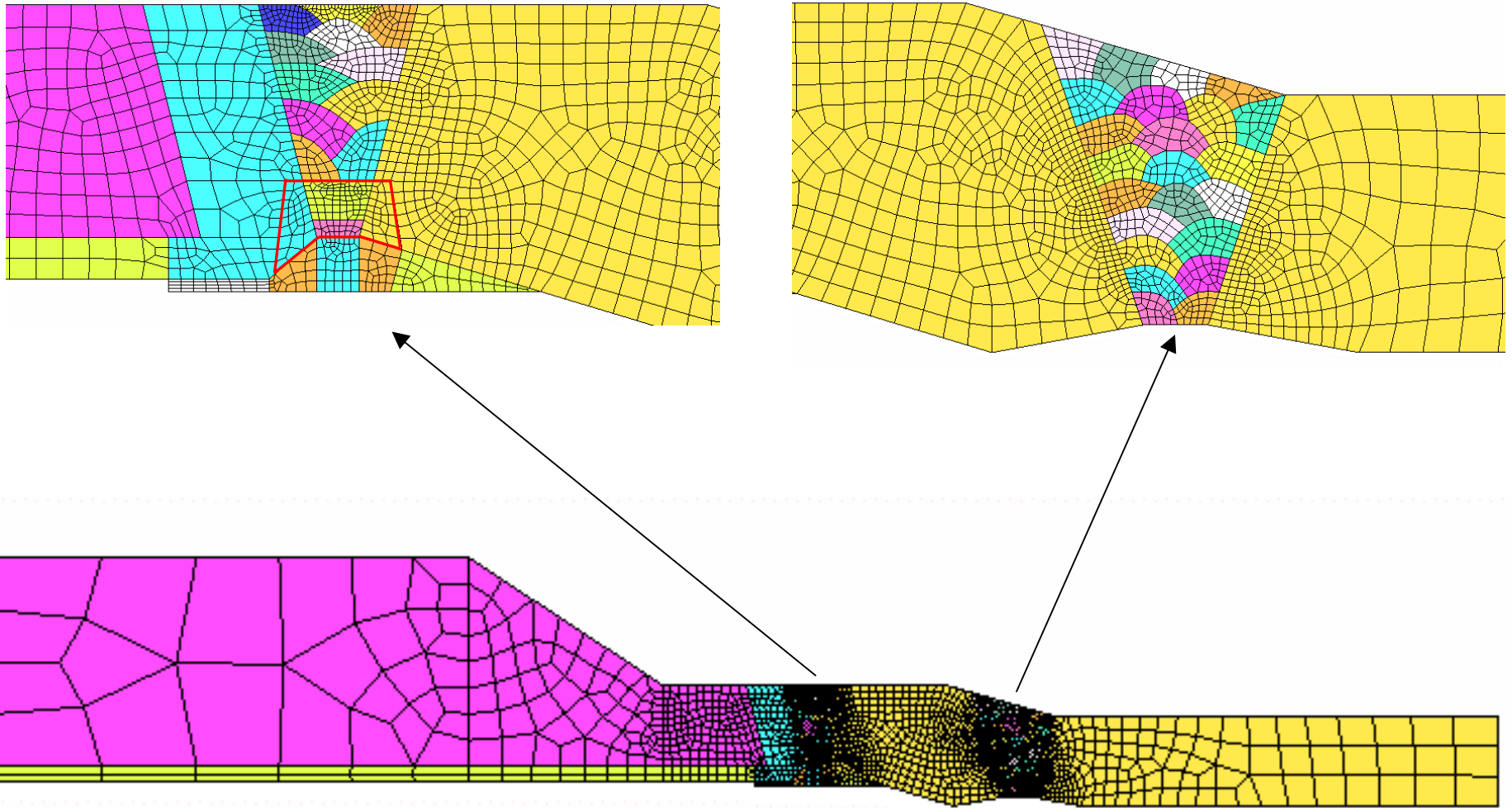
◆ *For confirmatory calculations, want to start with exact same geometry – DEI sent Surge nozzle geometry on 5/17, Relief nozzle geometry on 5/29*

◆ *With new information about ID last pass weld, should we consider spray nozzle WRS?*

Surge Nozzle Geometry from DEI



Surge-line Welding Residual Stress

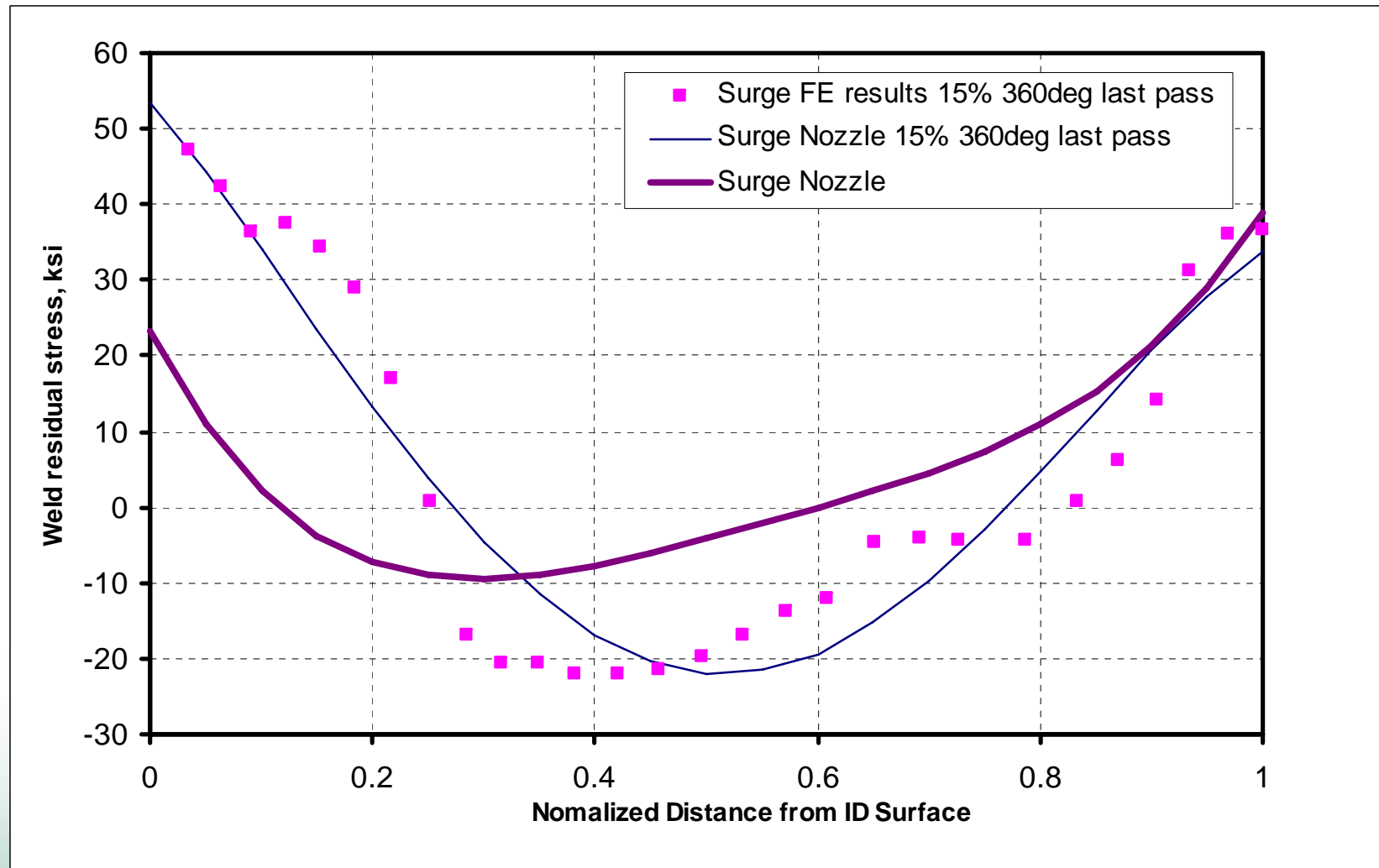


Surge-line Welding Residual Stress

- ***Surge WRS status:***
 - ◆ ***Mesh complete***
 - ◆ ***As of 5/30/07 – Thermal analyses underway***
 - ◆ ***Anticipated completion date: 6/7/07***

- ***Relief WRS status:***
 - ◆ ***Received geometry: 5/29/07***
 - ◆ ***Anticipated completion: 6/15/07***

Surge Nozzle Welding Results – original results



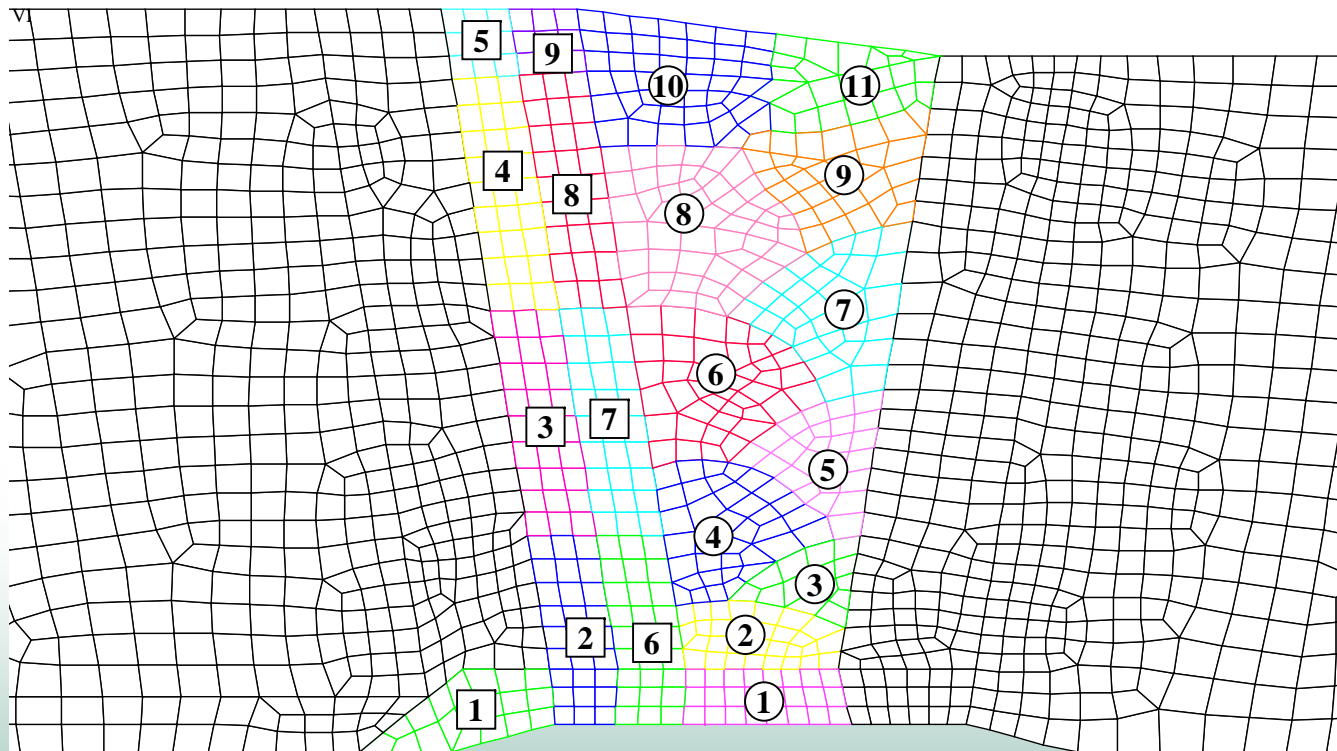
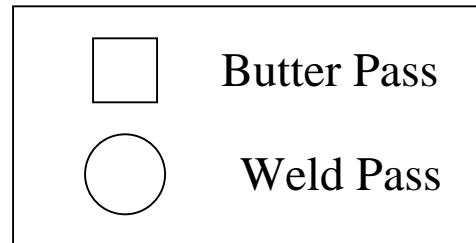
**2D Axi-symmetric analyses conducted –
Results used in scoping analyses**

Welding Repair Work – Battelle through MERIT

- ***Battelle (Bud Brust) conducted a surge nozzle WRS 3D solution to compliment 2D axi-symmetric solution generated earlier.***
- ***First conducted un-repaired (but still contains 15% - 360 last pass weld)***
- ***Then conducted 26% deep – 90degree weld repair***
- ***Results are welding stresses only***

Welding Repair Work – Battelle through MERIT

Preliminary



Geometry slightly different than analyzed in this effort

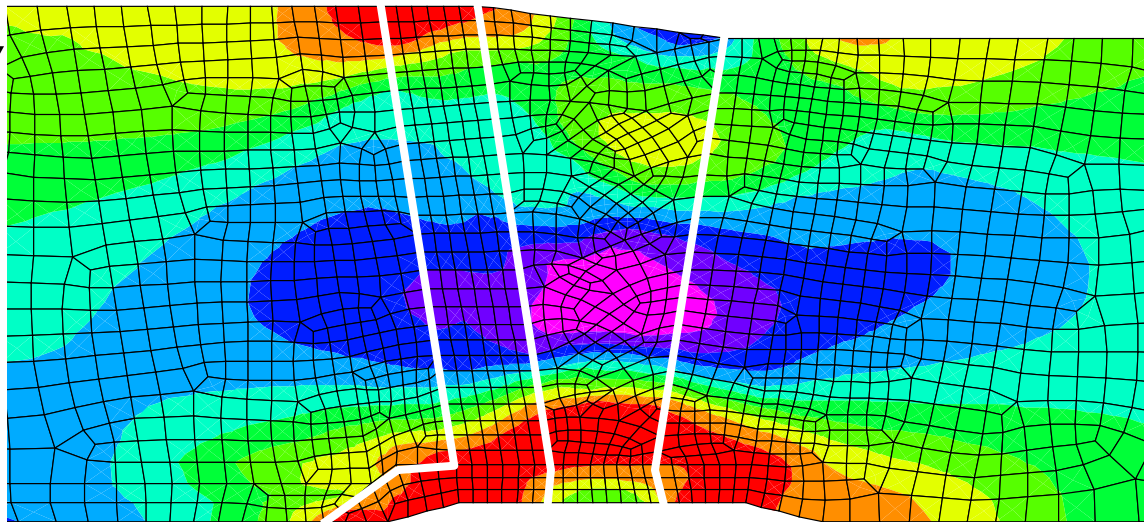
Emc²

Innovative Structural Integrity Solutions

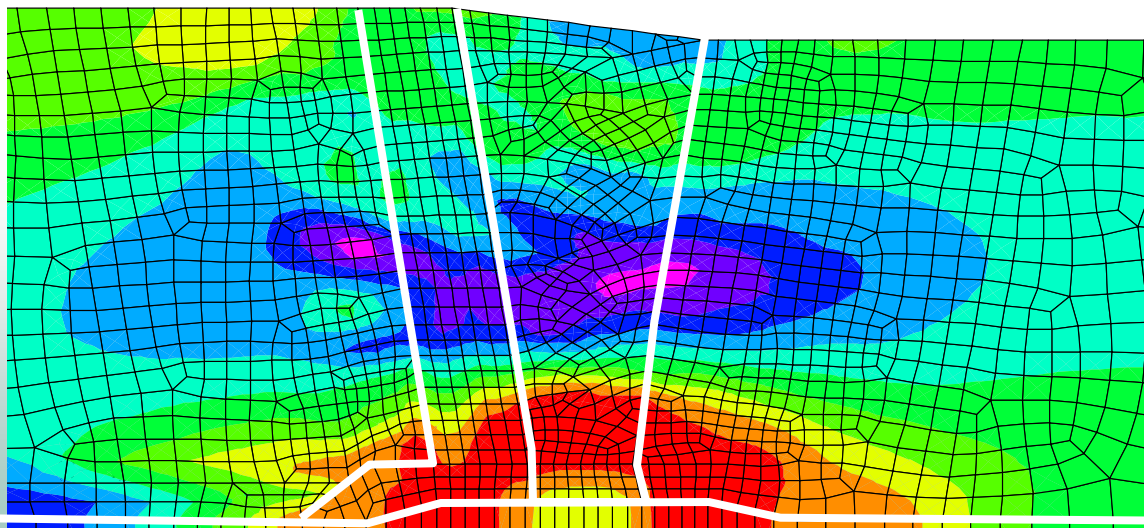
Axial Stresses – last pass 15%-360-Deg. weld

Preliminary

Axis-symmetric



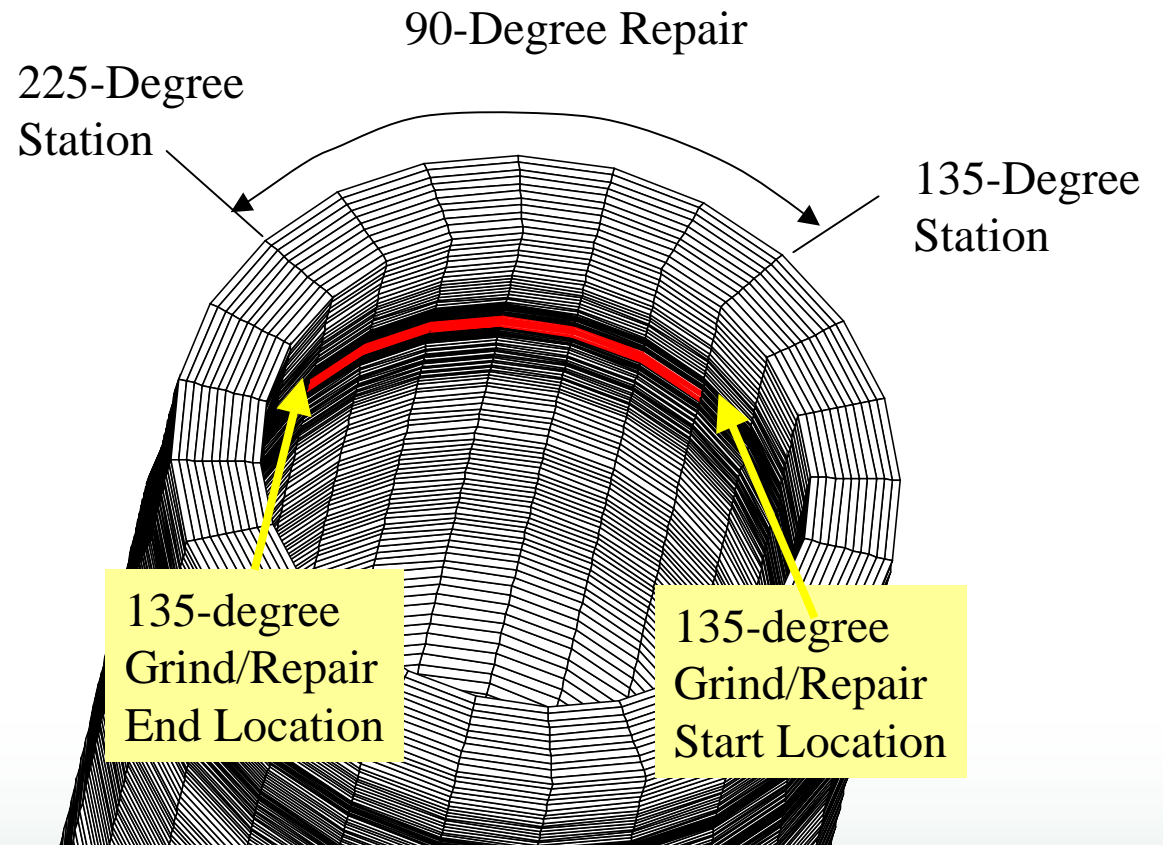
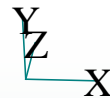
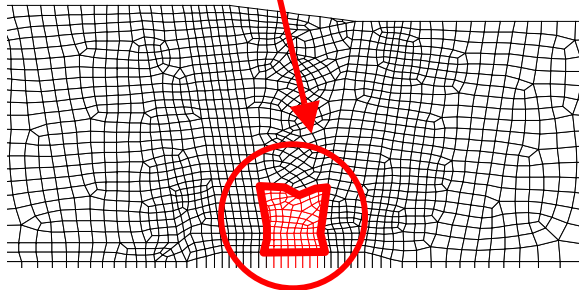
3D Solution
180-Degree
Location



Welding repair

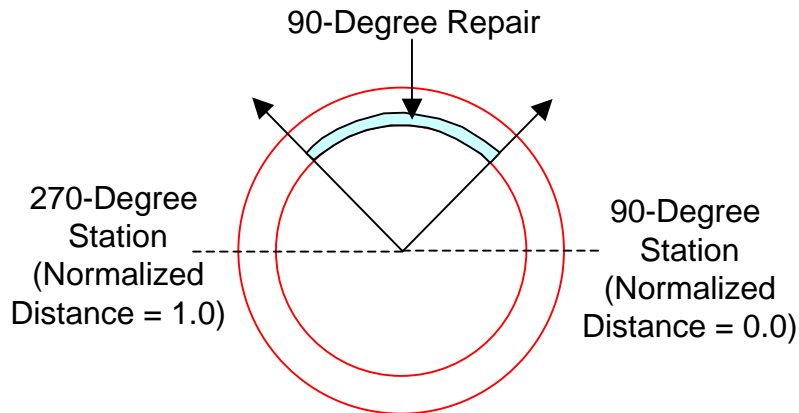
Preliminary

Repair Cross Section
(26% Through Thickness)



Comparison of Stresses Along Circumference

Preliminary

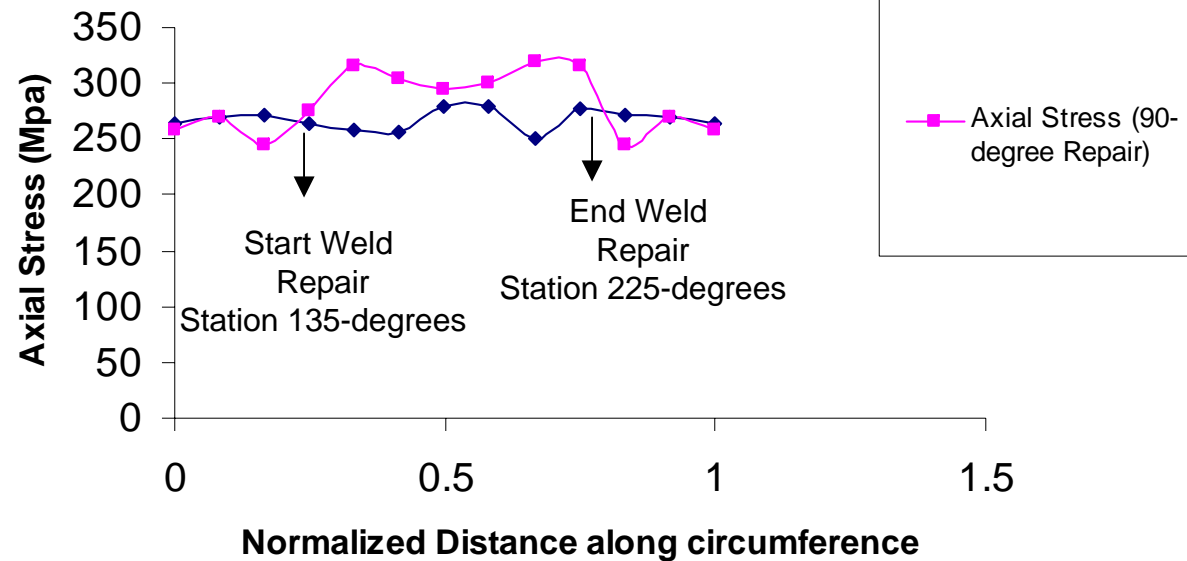


At a depth of 15%t

Surge - with and without 90-repair weld

Alloy 182

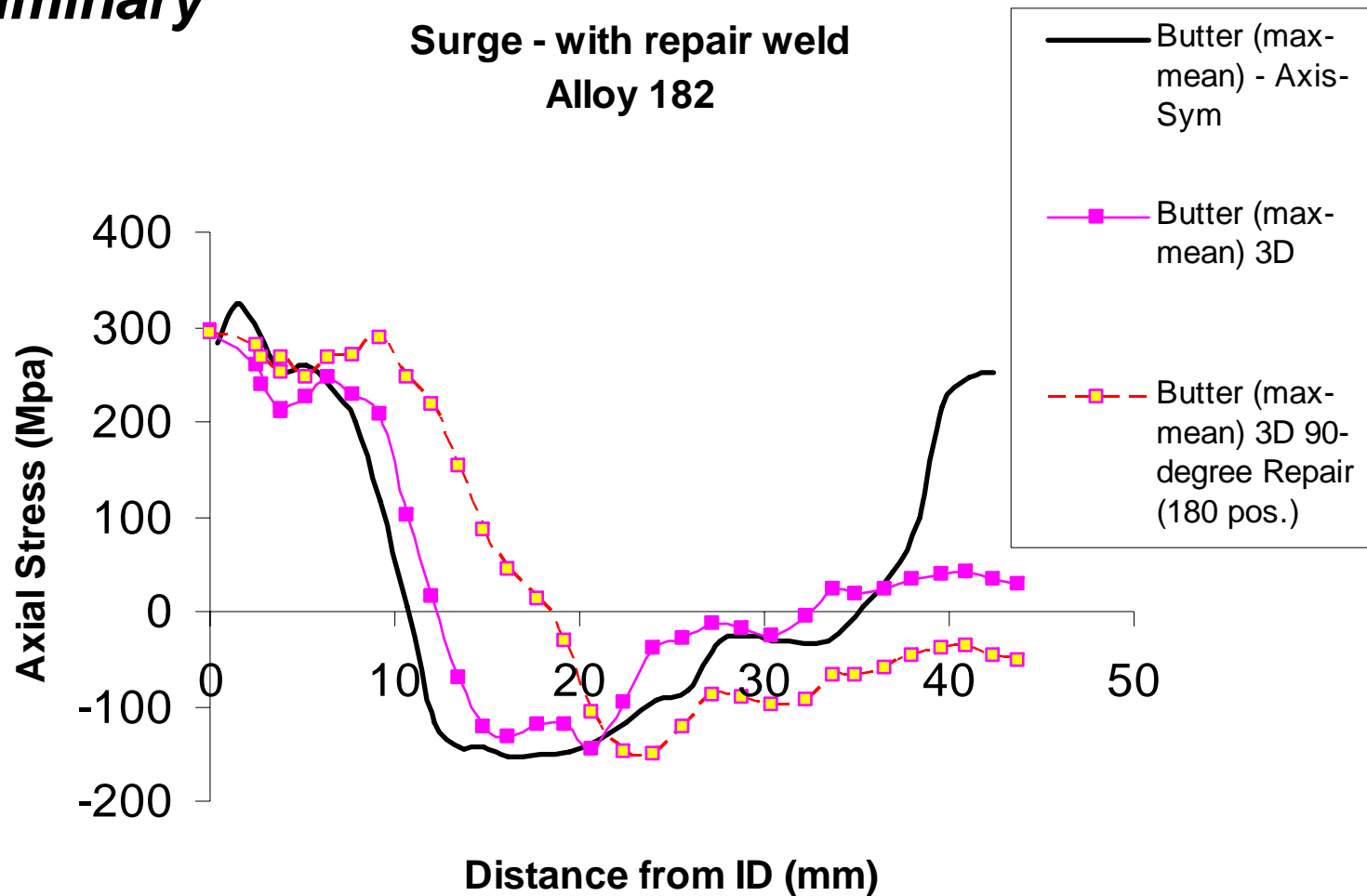
Stresses at Weld Centerline



Comparison With and Without Weld Repair

Preliminary

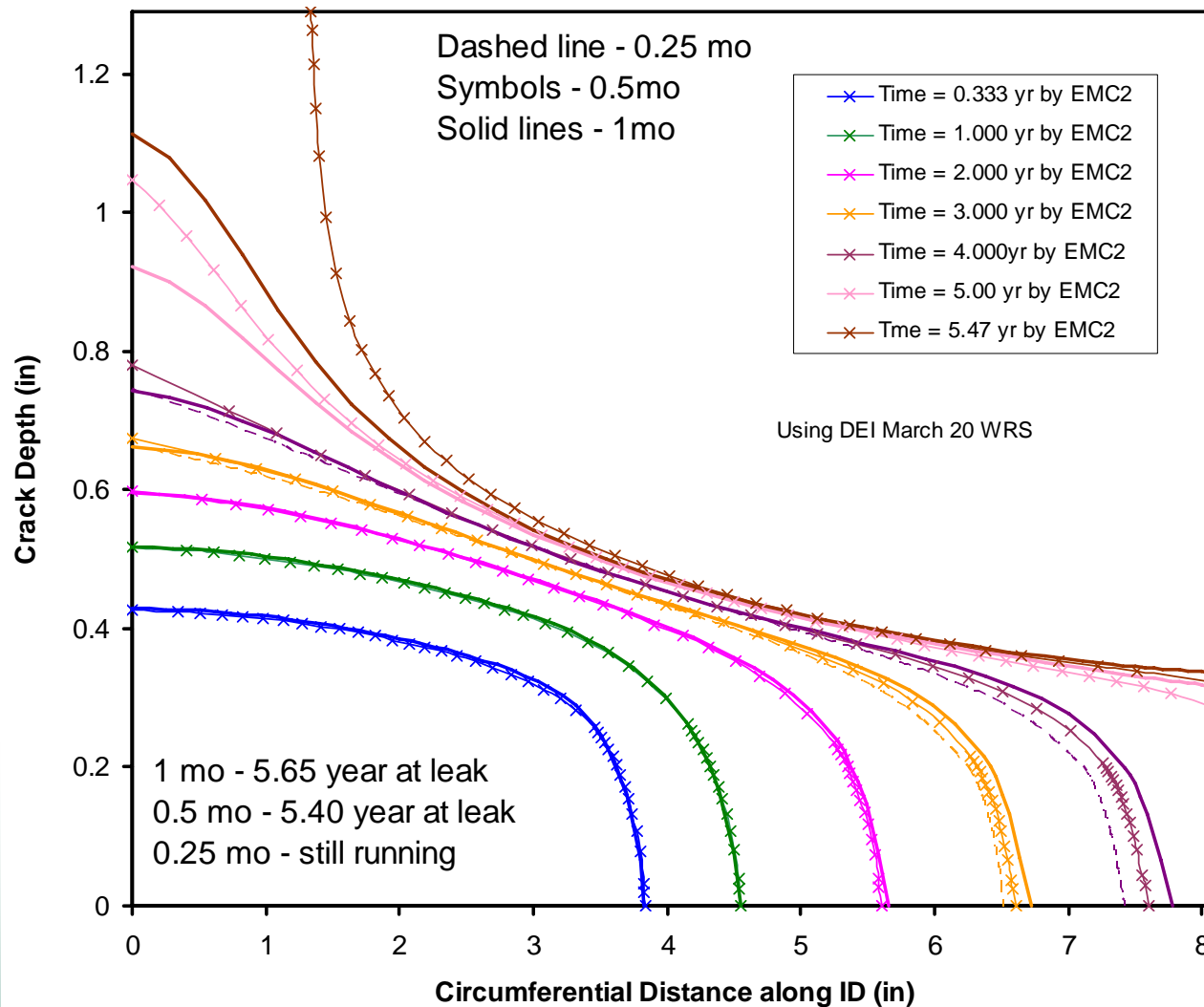
Surge - with repair weld
Alloy 182



Convergence Study

- ***Conducted additional Wolf Creek relief nozzle cases to investigate convergence***
 - ◆ ***1 month, 0.5 month and 0.25 month time steps***
 - ◆ ***Looked at fit to original relief WRS***
 - ◆ ***Looked at 65% bending moment***
- ***0.25 month time step still running, but appears converged at 0.5 month***
- ***Solution for time to leakage very sensitive to WRS***
- ***65% bending moment leaked at ~29 years***

Comparison of Time-to-Leak – DEI WRS

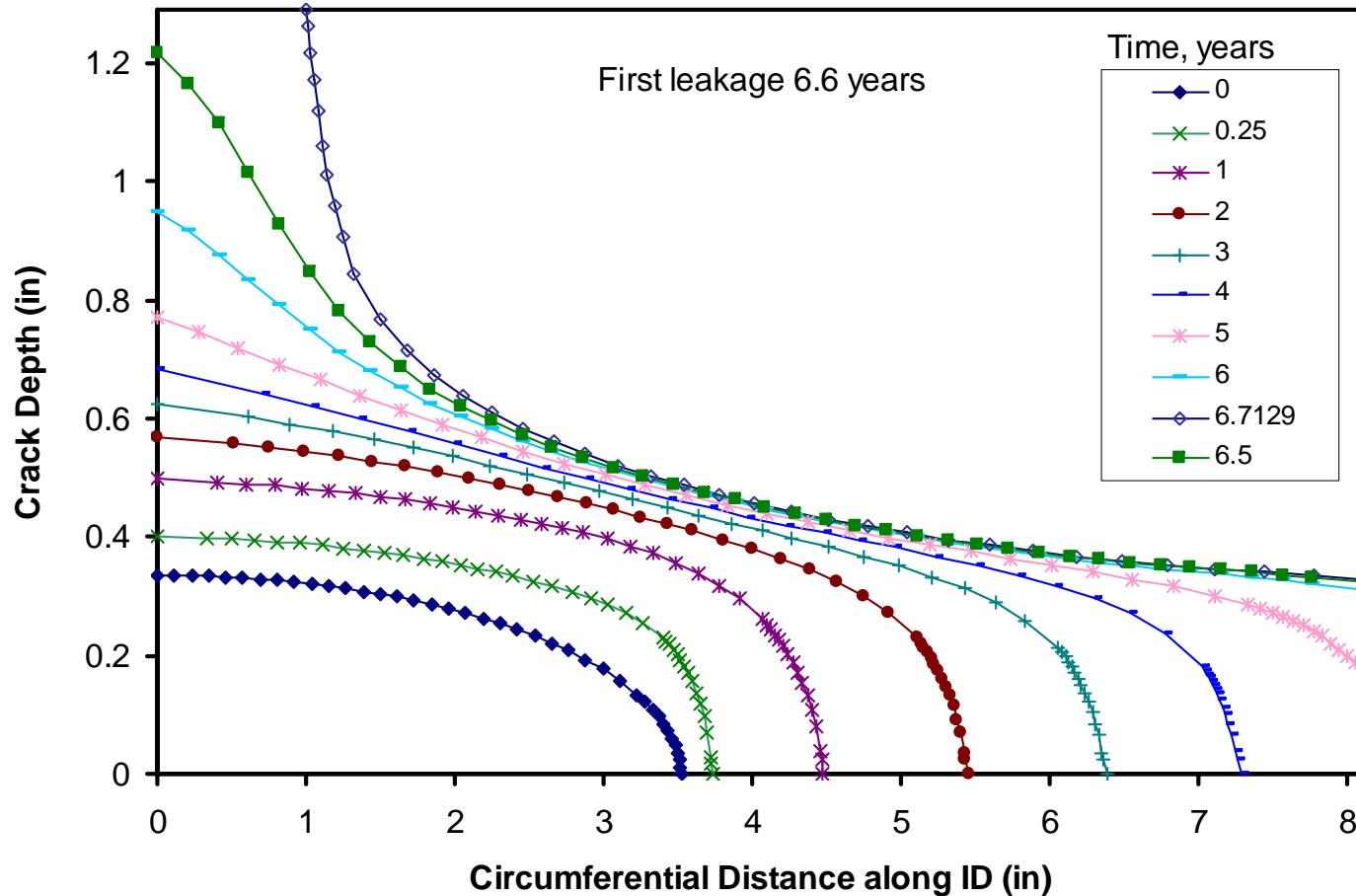


Using DEI March 20 WRS

Emc²

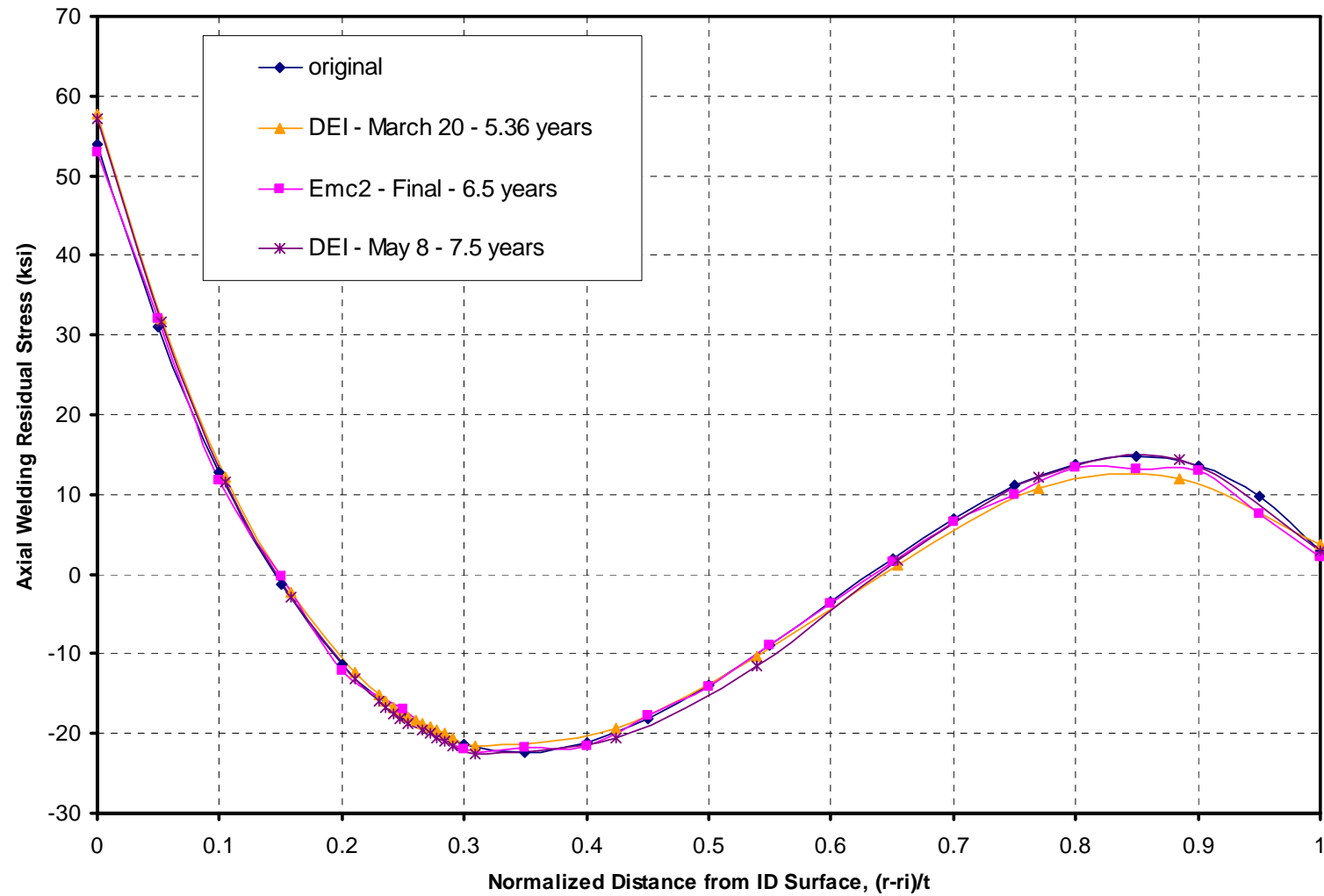
Innovative Structural Integrity Solutions

Comparison of Time-to-Leak – Emc^2 WRS

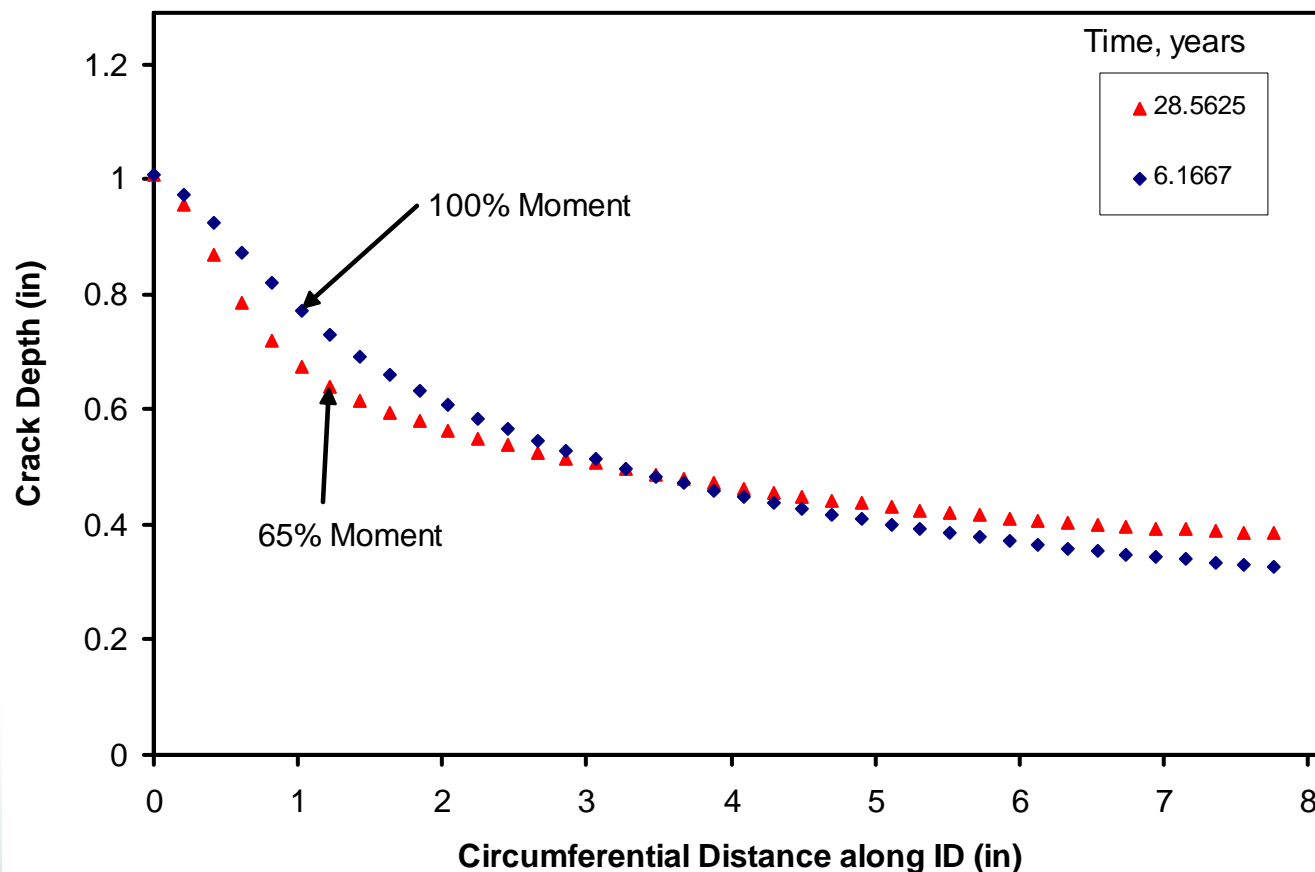


Using Emc^2 fit to relief nozzle scoping WRS

Comparison of WRS Estimation



Wolf Creek Relief with 65% Bending Stress

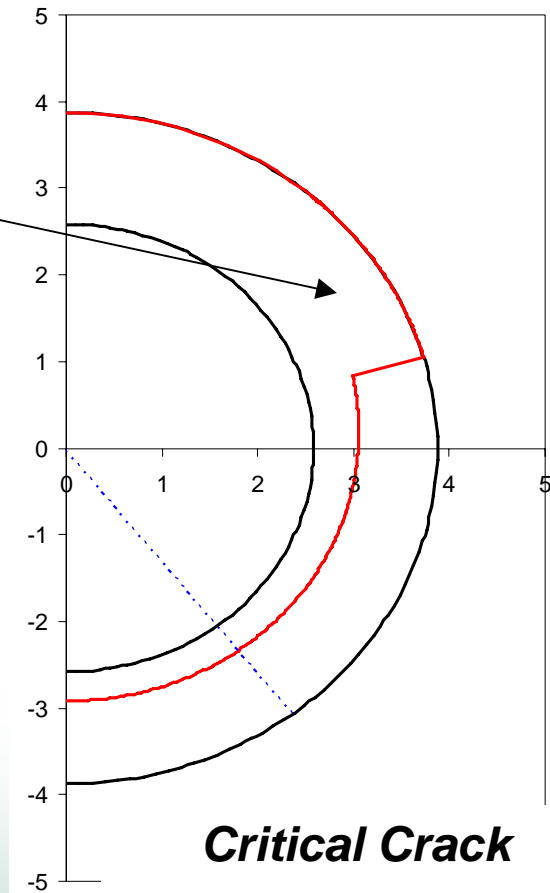
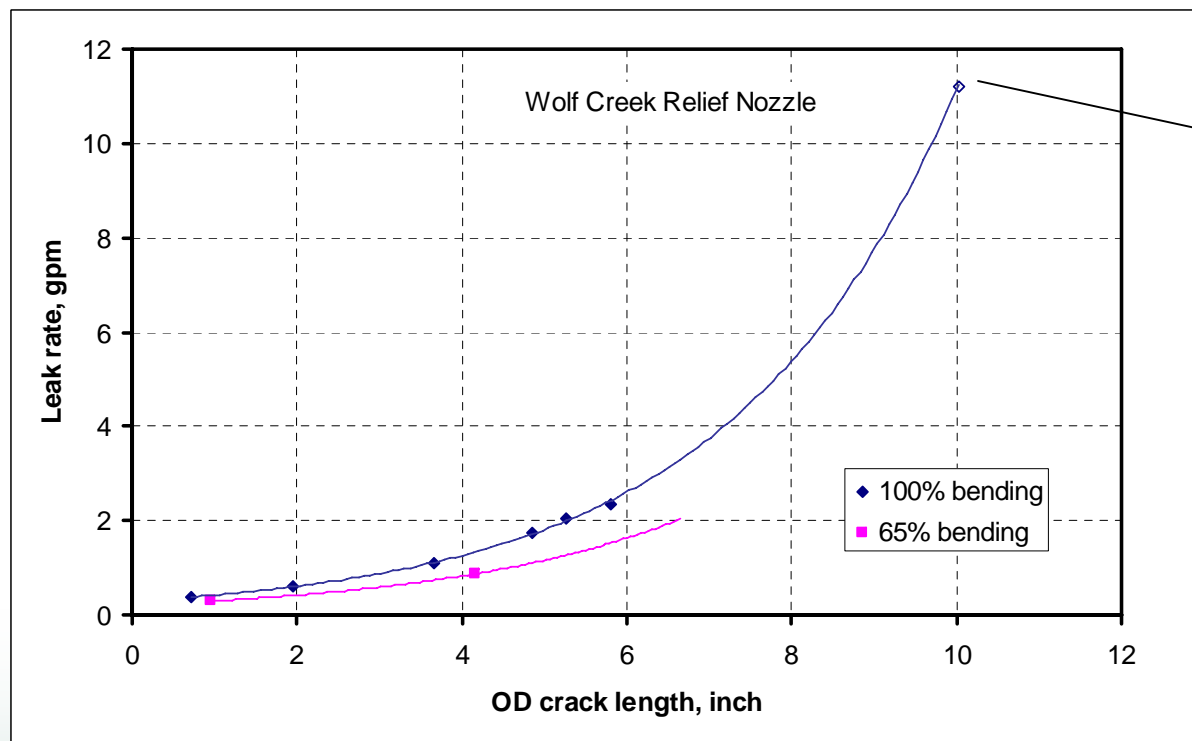


- **Conducted same analyses but with 65% bending stress**
- **Time to leakage = 29 years**
- **As surface crack penetrates wall, profiles similar**

Leak and Critical Crack Size Calculations

- ***Used Wolf Creek relief nozzle case – Emc^2 fit to WRS***
- ***Calculated leakage using SQUIRT,***
 - ◆ ***PWSCC crack morphology parameters, COD dependence***
 - ◆ ***Assumed elliptical opening***
 - ◆ ***COD from FEA***
 - ◆ ***100% quality steam***
- ***Used arbitrary NSC analyses with SS flow stress – with crack closure***
- ***Applied correction for limit load $1/0.85$ – Per earlier slides - $DPZP > 1$***
- ***Included all displacement controlled loads - conservative Emc^2***

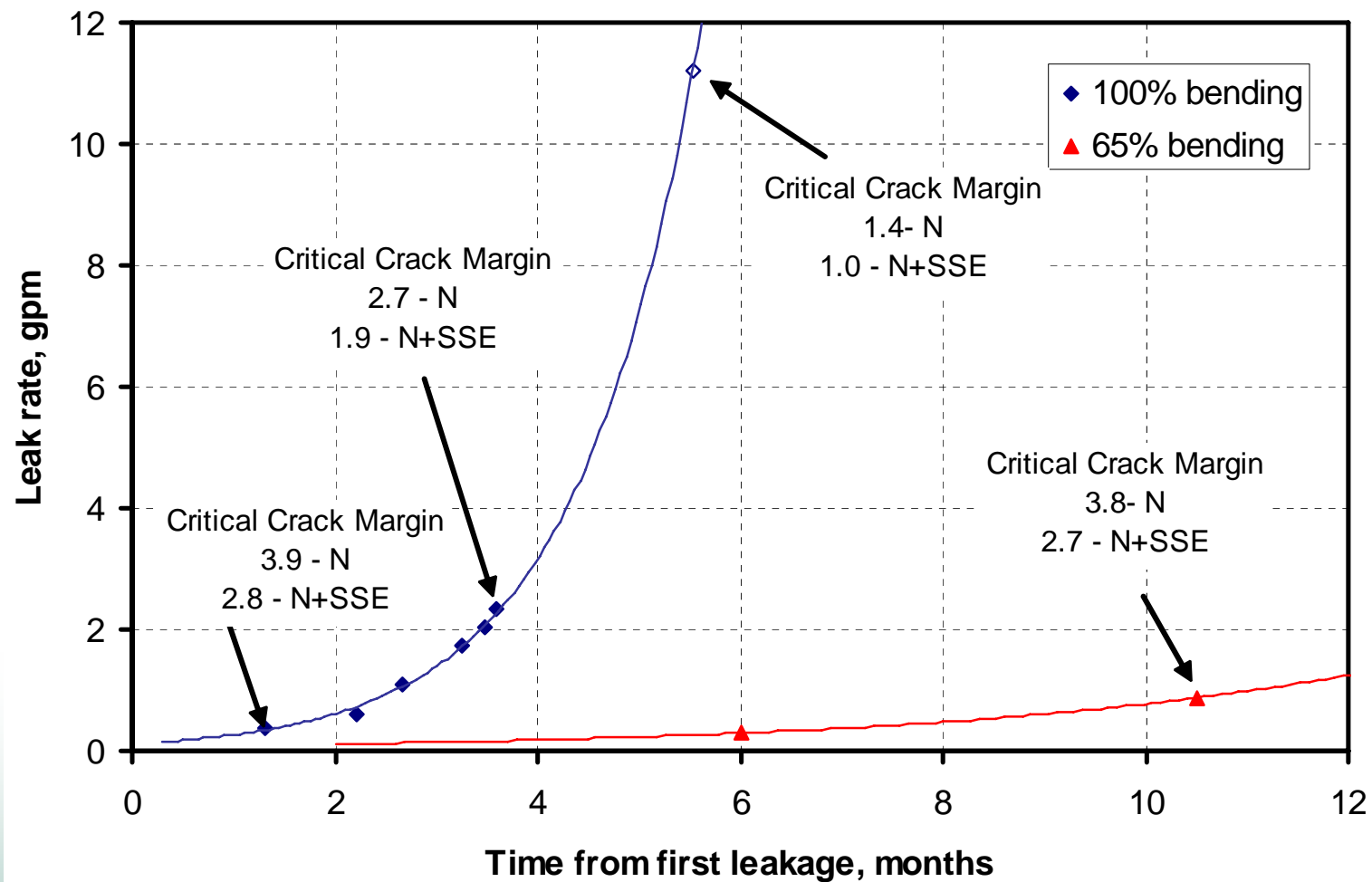
Leak Rate Results



**Critical Crack
Margin = 1 on N+SSE**

Preliminary

Wolf Creek Relief Nozzle Leak Rates



Preliminary

Plans + Tentative Schedule to Complete

- ***Review and verify secondary stress knock down factor – 6/8/2007***
- ***Finalize K verification – 6/8/2007***
- ***Continue WRS analyses – 6/15/2007***
- ***Confirmatory calculations for sensitivity matrix – 6/29/2007***
- ***WRS validation effort (Scope still need further refinement) – 7/31/2007***

Preliminary NRC Comments on the Industry Proposed Sensitivity Matrix



U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

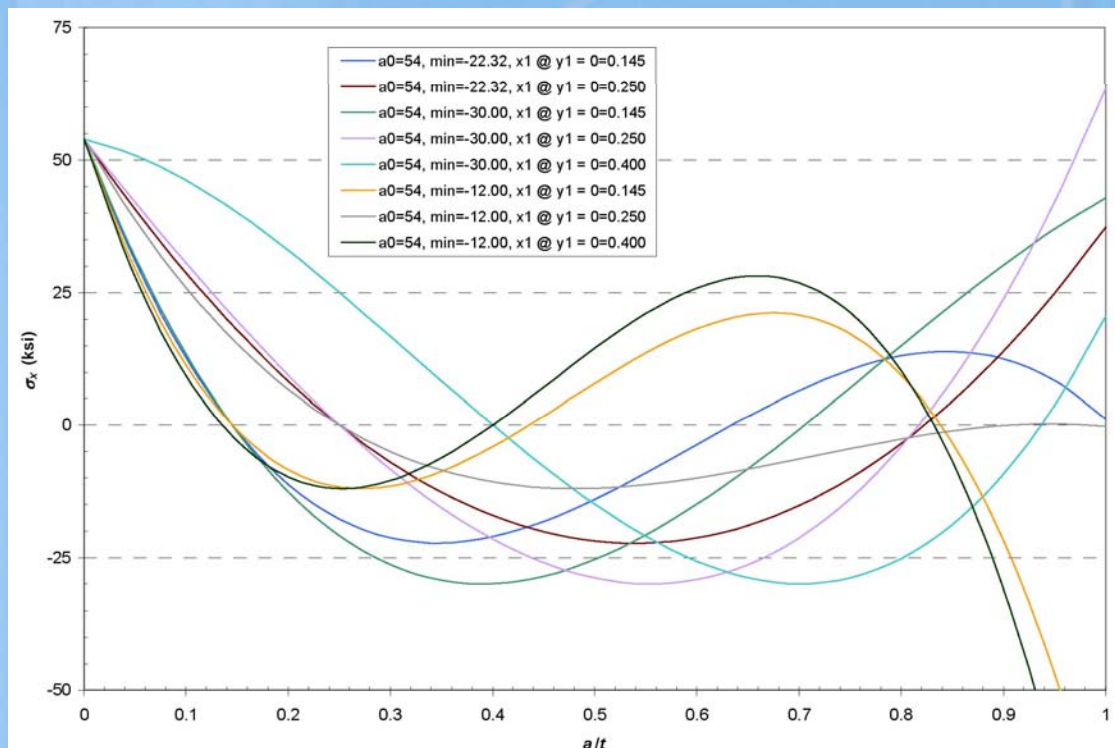
**E. Sullivan, S. Sheng,
D. Rudland, & Al Csontos
June 1, 2007**

Comments on the Industry Proposed Sensitivity Matrix

- Industry's proposed sensitivity matrix was well conceived, developed, and organized
- Proposed sensitivity matrix is a solid start
- A few more cases need to be evaluated:
 - Surge line with/without thermal expansion stresses
 - Cases 9 & 10 may need to use a revised WRS profile since the DMW/SS safe-end separation is large (6.8")
 - Evaluate an intermediate case between the "above arrest" and "high" P_b and $P_b/(P_m + P_b)$ for one or two configurations
 - Varying axisymmetric WRS profiles (*next slide*)
 - Other cases as results develop

Comments on the Industry Proposed Sensitivity Matrix

- Industry's April 9th presentation:
 - 26 axisymmetric, self-balancing WRS profiles
 - ID stress = 54 ksi



Comments on the Industry Proposed Sensitivity Matrix - Outputs

- PICEP and SQUIRT leak rate models provide mean values and may need to be evaluated either through sensitivity or safety factors for:
 - Detectable leakage
 - Maximum leakage prior to rupture
- NRC staff does not understand why the time from initial flaw to rupture should be compared to the operating age of each subject plant?
- NRC staff does not understand why varying the 8 sensitivity parameters can be related to the operating age of each subject plant?

Pressurizer Nozzle Fabrication History (DRAFT)

Plants C and F
Cameron Martin

Wolf Creek Task Group Meeting
May 31 – June 1, 2007

DRAFT: Plant C

Pressurizer Nozzle Repair History

Repair Number	Part Description	Defect Description	Repair Description
1	Surge nozzle weld buildup	Porosity in weld; rejected by RT	Removed defect, PT, then repaired weld (twice) with Alloy 182
2	Safe end to surge nozzle weld	Welded safe end to nozzle with wrong weld procedure	See repair #5
3*	Surge nozzle cladding	PT of cladding; one indication after PWHT	Repaired by temper-bead with 309 and 308 stainless steel.
4*	Safe end to surge nozzle weld	Rejected for weld defects per RT	Removed defects, repaired weld with Alloy 182.
5*	Safe end to surge nozzle weld	In Repair #2 the incorrect weld procedure was used to weld the safe end to the surge nozzle.	Removed and replaced safe end. Reattached safe end to nozzle with Alloy 82/182.
6	Spray, safety & relief nozzles (A, B, C, D and E)	Bores of upper head nozzles are too large to permit proper gaps and seating of liners.	Weld build-up the oversized bores using 308L Stainless Steel. Then bores machined to size.
7	Spray, safety & relief nozzles (A, B, C, D and E)	After “#6” repairs and machining, bores remain slightly oversized with respect to the liner outside diameter.	Accept size as-is; liners rolled into place.
* - Repair number's 2 and 4 are irrelevant because the safe end to surge nozzle weld was completely replaced in repair number #5.			

DRAFT: Plant C (continued)

Pressurizer Nozzle Repair History

Repair Number	Part Description	Defect Description	Repair Description
8	Spray, safety & relief nozzles (A, B, C, D and E)	Lengths of liners are greater than the design dimensions. Can't get proper seating; gap too large.	Cut and re-installed liners to ensure best possible seating; rolled using standard procedures.
9	Safety/relief nozzle "C"	Safe end was mis-machined; incorrect angle	Accepted as-is; main deviation on outside angle.
10	Safe end to Safety/relief nozzle "A" weld	RT located defect in the safe-end attachment weld; occurred at interface of weld and buttering	Ground out defect repaired by temper bead using Alloy 182.
11	Safety/relief nozzle "C" cladding and weld	PT indications on cladding of the nozzle and at safe-end attachment weld	Removed safe-end and repaired build up with Alloy 182. The build up was then PWHT. The safe end was then reattached to the nozzle using Alloy 82/182.

DRAFT: Plant F

Pressurizer Nozzle Repair History

Repair Number	Part Description / Test No.	Defect Description	Repair Description
1	Spray Nozzle E	Grinding of R.T. defects in nozzle to safe-end weld caused base metal 1/8"W x 1/2"D x 6"L to be exposed after PWHT.	SS safe end cut off. Butter machined off to original base metal. Etched surface. Re-build up butter with Alloy 182. See Repair #2.
2*	Spray Nozzle E	1. Defects in machining of build-up (butter) including 1/32" step in bore ID located 1 5/16" down from lip & blending on OD at bond line. 2. Final machining done prior to PWHT (rather than after PWHT). 3. Safe end length = 4.61" is out of tolerance.	1. Lightly blended out step defect in build-up while maintaining wall above minimum. R.T. accepted. See Repair #3. 2. Local PWHT.. 3. Weld build-up end of short safe end with 308L stainless steel.
3*	Spray Nozzle E	Nozzle Build-up (butter) P.T. indications due to porosity. Grinding of indications after PWHT exposed base metal. Wall was not reduced.	Bead temper repaired part of the exposed base metal cavity with Alloy 182. Then completed the weld repair with Alloy 82. See Repair #4.
4*	Spray Nozzle E	Nozzle Build-up (butter) R.T. rejected areas. Indications run 360° around nozzle for a depth of 9/16" from I.D.	Defect was removed. X-ray showed linear indications remained, depth of 1/2". R.T. rejected. See Repair #5.
5*	Spray Nozzle E	Nozzle Build-up (butter) R.T. rejected areas. Indications remained.	Ground additional 1/8" at upper wall only. X-ray showed traces of original indications in some areas. R.T. rejected. See Repair #6
* - Repair number's 2, 3, 4, 5, 6, 7, 9, and 10 are irrelevant because the spray nozzle weld build up underwent repair and PWHT in repair number 11.			

DRAFT: Plant F (continued)

Pressurizer Nozzle Repair History

Repair Number	Part Description / Test No.	Defect Description	Repair Description
6*	Spray Nozzle E	Nozzle Build-up (butter) R.T. rejected areas. Some indications remained.	Ground additional 3/16". R.T. of cavity accepted. See Repair #7.
7*	Spray Nozzle E	Nozzle Build-up (butter) P.T. rejected. Base metal exposed 360° x 0.5" W x 0.375" D at bond line. Sketch with size and location.	Machined off Inconel build-up, etched surface and recorded dimensions. See supplement 1.
8	Spray Nozzle E	Nozzle dimensions out of tolerance after removal of Build-up (butter).	Weld repaired nozzle to restore nozzle length with Alloy 182. See Repair #9.
9*	Spray Nozzle E	Nozzle Build-up dimensions out of tolerance after machining.	Weld Build-up restored to drawing dimensions including tie-in weld with Alloy 182. See Repair #10
10*	Spray Nozzle E	Nozzle Build-up needs repair of P.T. indications before PWHT. No base metal exposed.	Areas ground and weld repaired with Alloy 82. See Repair #11.
11*	Spray Nozzle E	Nozzle Build-up needs repair of remaining P.T. indications before PWHT. No base metal exposed.	Areas ground and weld repaired with Alloy 82. Local PWHT. Welded safe end to nozzle with Alloy 82/182.
* - Repair number's 2, 3, 4, 5, 6, 7, 9, and 10 are irrelevant because the spray nozzle weld build up underwent repair and PWHT in repair number 11.			

Conclusions

- Plant C
 - No I.D. DM weld repairs
- Plant F
 - Spray Nozzle
 - Final repair to nozzle buttering included local PWHT