Initial Project Review Meeting:
Advanced FEA Crack Growth Calculations for Evaluation of PWR Pressurizer Nozzle Dissimilar Metal Weld Circumferential PWSCC

Sponsored by: EPRI Materials Reliability Program

Slide Handout Package to Support Expert Discussions

Presented To:
Expert Review Panel for Advanced FEA Crack Growth Calculations

Presented By:

Glenn White
John Broussard
Dominion Engineering, Inc.

March 7, 2007
Meeting on Implications of Wolf Creek Dissimilar Metal Weld Inspections
Bethesda North Marriott Hotel and Conference Center
North Bethesda, Maryland

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Topics

- Agenda
- Project Objective
- Background
- Previous Analysis: White Paper Section 5 Calculation
- Project Plan:
  - Task 1: Software Development (*incl. separate presentation by Ted Anderson , Quest Reliability, LLC*)
  - Task 2: Phase I Calculation
  - Task 3: Phase II Calculations
  - Optional Task 4 Calculations
- Eight Initial NRC Comments
- Discussion of Proposed Technical Approach

Meeting Agenda

- Morning (industry meeting)
  - Introductions
  - Review of agenda and project objective
  - Project background and previous White Paper calculation
  - Review of project plan
  - FEACrack background and software enhancements (Ted Anderson, Quest Reliability, LLC)
  - Detailed technical discussion of proposed technical approach (guided by this presentation)
- Afternoon (industry meeting / public NRC meeting)
  - NRC presentation
  - Industry (MRP/EPRI/NEI) project status presentation
  - Continuation of detailed technical discussion of proposed technical approach
  - Communication protocol
  - Meeting wrap-up and summary

Principal Meeting Participants

- EPRI Project Management / Support
  - Craig Harrington, EPRI
  - Tim Gilman, Structural Integrity Associates
- Project Team
  - Glenn White, Dominion Engineering, Inc.
  - John Broussard, Dominion Engineering, Inc.
  - Ted Anderson, Quest Reliability, LLC
- Expert Review Panel
  - Warren Bamford, Westinghouse
  - Al Csontos, NRC Research
  - Bob Hardies, NRC Research
  - David Harris, Engineering Mechanics Technology
  - Pete Riccardella, Structural Integrity Associates
  - Dave Rudland, EMC2
  - Ted Sullivan, NRC NRR
  - Ken Yoon, AREVA

Meeting Objectives

- The objectives of this meeting are to
  - Continued communication with NRC with regard to developments related to implications of the Wolf Creek indications reported in October 2006
  - Collect technical input from the industry and NRC experts on the project technical approach
  - Reach consensus of the expert review panel on specific technical approach items wherever possible
  - In other cases, identify appropriate path to resolution of technical approach items

Project Objective

- Evaluate the viability of through-wall leakage prior to rupture for the pressurizer nozzle dissimilar metal (DM) welds in the group of 9 PWRs scheduled to performed PDI inspection / mitigation during the spring 2008 outage season given the potential concern for growing circumferential stress corrosion cracks

Project Approach

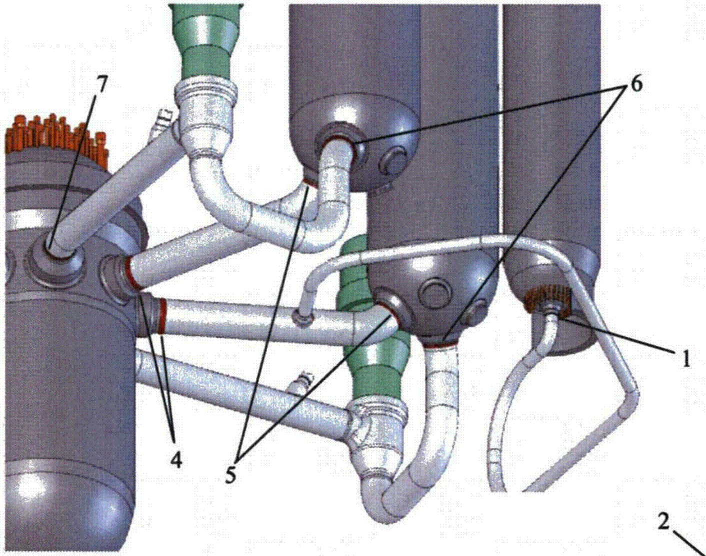
- The basic approach is to perform fracture mechanics based crack growth calculations for surface and through-wall circumferential flaws using advanced finite-element analysis software (FEACrack), with
  - Growth at each point on the crack front as a function of the stress intensity factor calculated at that point
  - Verification of the numerical accuracy of the fracture mechanics calculations
  - Consideration of geometry and load parameters for group of subject welds
  - Sensitivity cases to consider the range of potential welding residual stress distributions, and consideration of residual stress redistribution with crack growth
  - Critical crack size calculations to define the end point for the crack growth calculation
  - Appropriate consideration of modeling uncertainties
  - Consideration of the potential for multiple flaws
  - Validation of the model versus available data
  - Expert panel input and review throughout the project

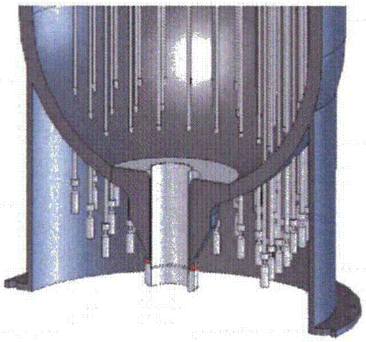
Background

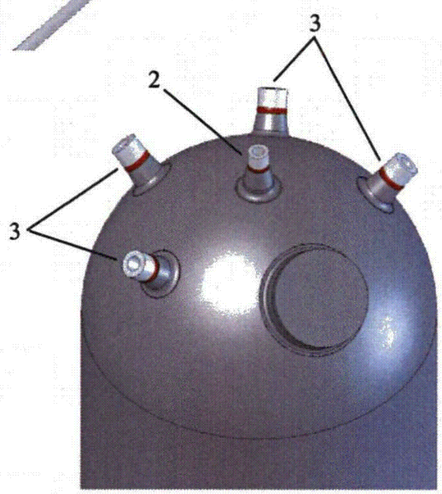
- Background
  - PWR Pressurizers
  - Options for PWSCC Crack Growth Calculations
  - Welding Residual Stress (WRS)
  - Fracture Mechanics with WRS Redistribution
  - MRP-115 Crack Growth Rate Equation

Background
PWR Pressurizers

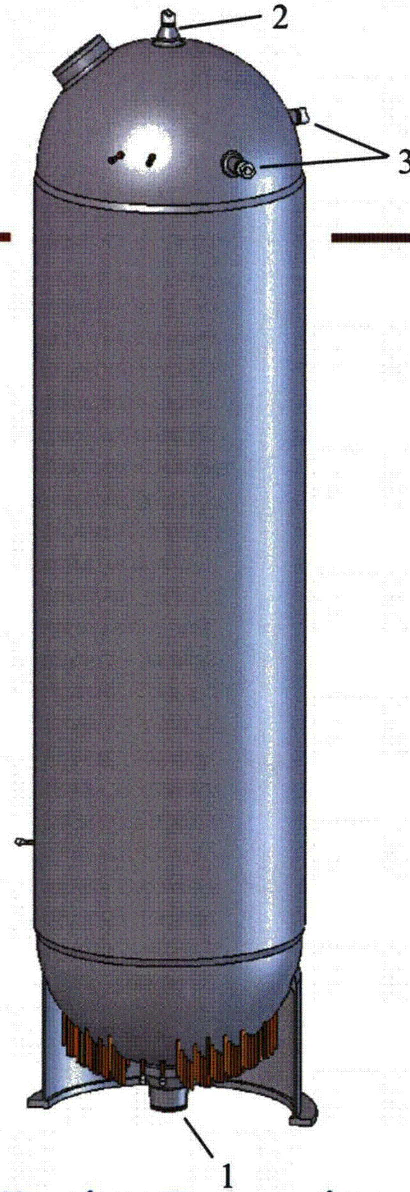
1. Surge Nozzle
2. Spray Nozzle
3. Safety/Relief Nozzle







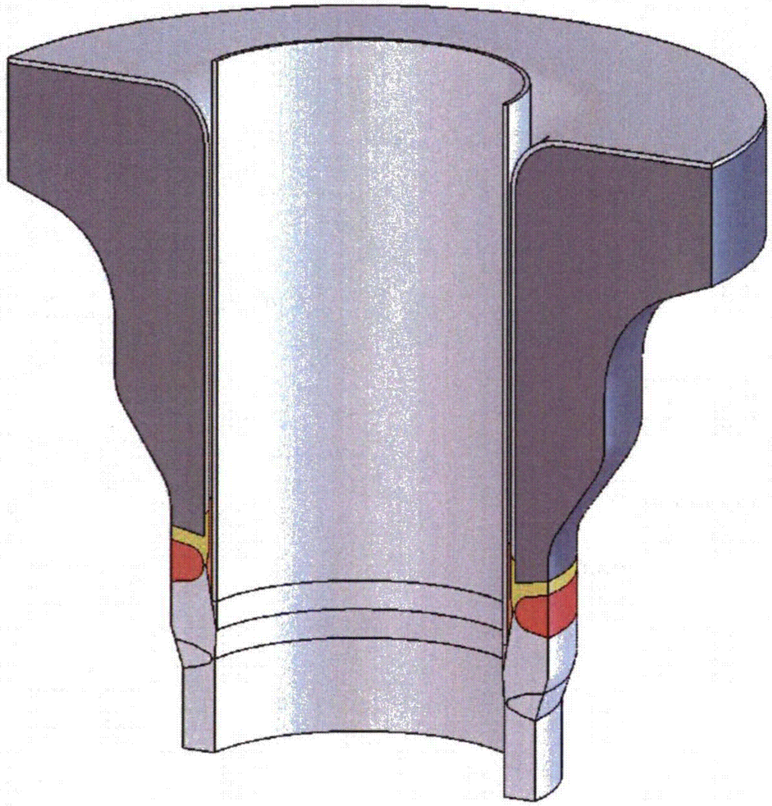
Example Westinghouse Design Pressurizer



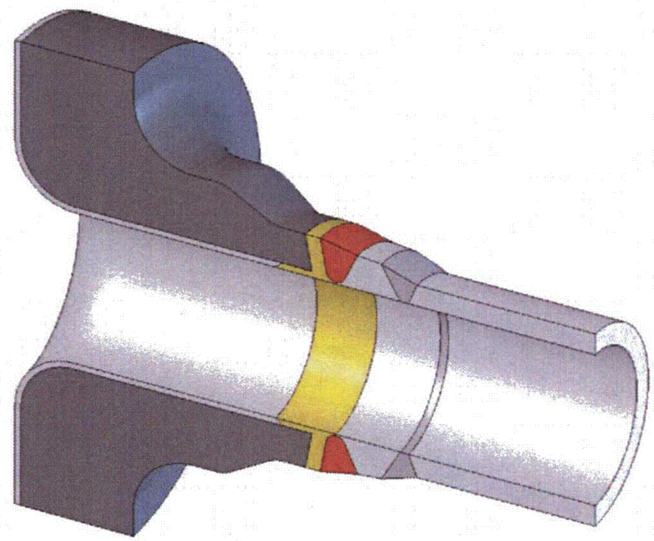
Example CE Design Pressurizer

Background
PWR Pressurizer Nozzles

Source: *MRP 2007-003 Attachment 1 (White Paper).*



Example Pressurizer Surge Nozzle



Example Pressurizer Safety/Relief Nozzle

Background

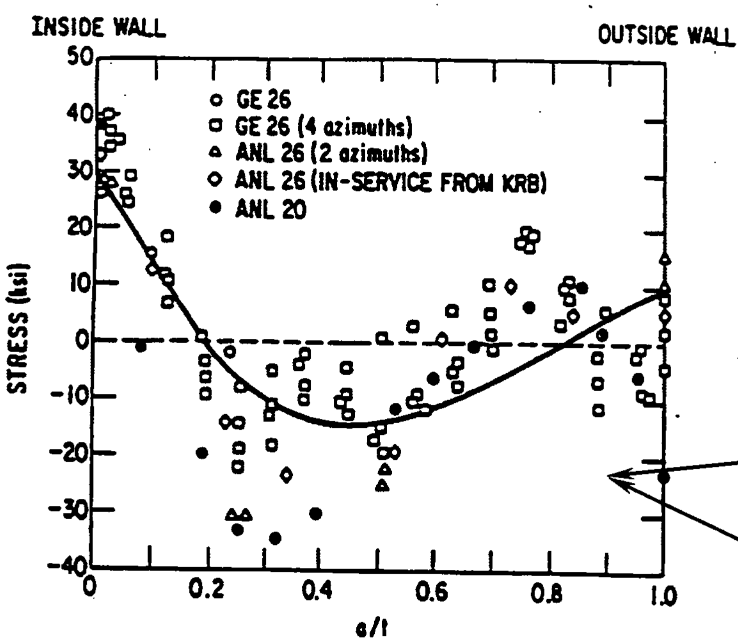
Options for PWSCC Crack Growth Calculations

Main Analysis Inputs	Environment *Primary Water* *Temperature*	Weld Design and Material Properties	Fabrication *Welding* *Weld Repairs*	Applied Loads *Pressure* *Hydro Test* *Forces & Moments* *Diff. Thermal Exp.*
Stress Analysis	Classical Strength of Materials (Superposition) *Weld Residual (Generic)* *Pressure* *Forces & Moments* *Diff. Thermal Exp.*	Finite Element Stress Analysis (FEA) *Weld Residual* *Weld Repairs* *Pressure* *Forces & Moments* *Diff. Thermal Exp.* *Stress Relaxation/Relief*		
Fracture Mechanics (Stress Intensity Factor) Analysis	Analysis Algorithm Newman-Raju, Zahoor, or ASME A-3000 *Fit Cubic Distribution to Stress through Centerline of Crack*	"Superposition" Finite Element Method *Apply Crack Face Pressure Based on Stress FEA*	Finite Element Method *Map 3D Stress Field into Fracture Mechanics Model and Integrate J*	
Crack Growth Model	Factor Times "Scott Model"	Curve with or without Stress Intensity Factor Threshold	"Plateau" Curve	Bi-Linear Envelope

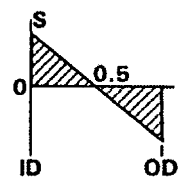
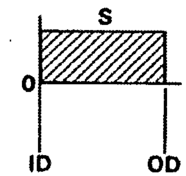
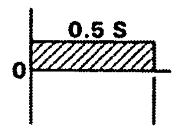
Background

Welding Residual Stress (WRS)

- Generic residual stress models established by testing
  - Most results were for thinner wall BWR piping
  - Generic models based on nominal fit of test data



NUREG-0313, *Technical Report on Material Selection and Processing Guidelines for BWR Coolant Pressure Boundary Piping: Final Report*

Wall Thickness	Through-Wall Residual Stress[1]	
	Axial	Circumferential[2]
< 1 inch		
≥ 1 inch	See Note 3	

[1]S = 30 ksi

[2]Considerable variation with weld heat input.

[3]$\sigma = \sigma_i\,[1.0 - 6.91(a/t) + 8.69(a/t)^2 - 0.48(a/t)^3 - 2.03(a/t)^4]$

σ_i = stress at inner surface (a = 0)

"Evaluations of Flaws in Austenitic Piping," *Transactions of ASME, J. of Pressure Vessel Technology*, v. 108, Aug. 1986, pp. 352-366.

Background
Welding Residual Stress (WRS) (cont'd)

- Welding residual stresses are high and a significant contributor to butt weld PWSCC
- The generic welding residual stress model is conservative for the as-designed case without repairs
- Weld repairs from the ID surface (360° or partial-arc) significantly increase ID surface stresses
  - Generic welding residual stress model does not bound FEA results for cases involving repairs from the ID surface
- <u>Deep partial-arc</u> weld repairs from the OD surface have high restraint and may produce similar through-wall stress distributions as for cases of ID repairs depending on depth of repair
  - Generic welding residual stress model does not bound FEA results for some cases involving partial-arc repairs from the OD surface
- High stresses for cases involving partial-arc repairs are limited to the repaired area
  - Expected to produce cracks limited to the repaired area, not 360°

Background

Fracture Mechanics with WRS Redistribution

- Stress intensity factors are often calculated using superposition method
- For cases with high residual stresses, superposition
  - Conservatively applies residual stresses as primary loads
  - Does not allow for stress relaxation and redistribution with crack growth
- Development work was performed to modify the existing stress analysis model to calculate J-integrals including the effects of stress relaxation with crack growth
- J-integral is appropriate for treatment of crack growth driven by local residual stresses as it reflects the energy release rate, not just the stress singularity at the crack tip due to remote loading

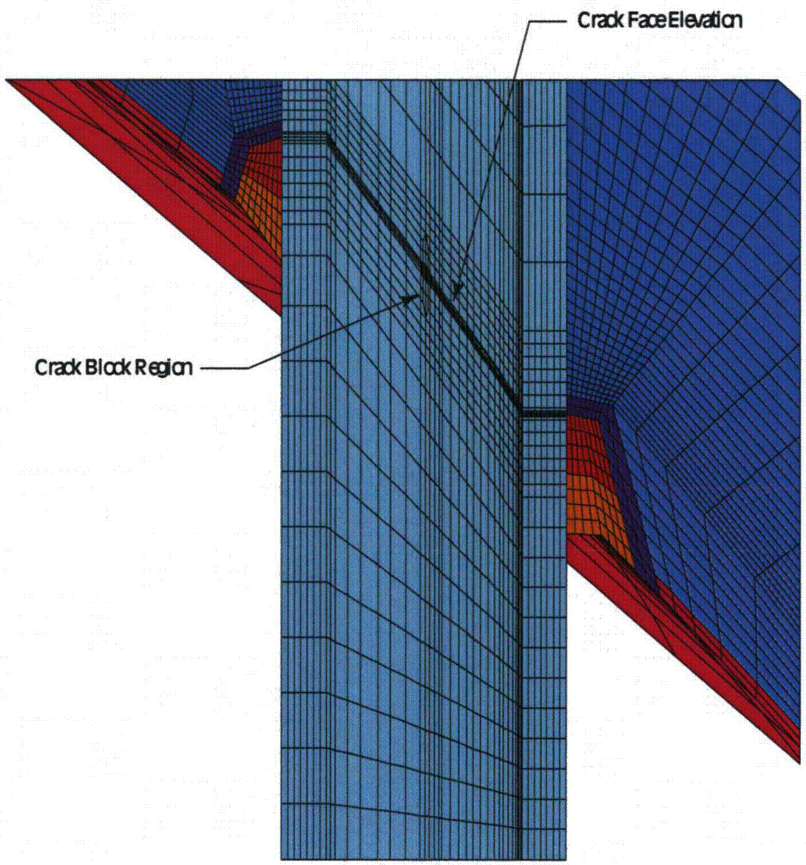
Fracture Mechanics with WRS Redistribution
Calculation Methodology

- Initial application was for through-wall crack in outer row CRDM nozzle parallel to weld contour with variable distance above top of weld
- Custom fracture mechanics code added to DEI welding residual finite-element stress model
- Stress redistribution from intact to cracked conditions modeled
  - Redistribution modeled as an elastic unloading problem amenable to LEFM
- Equivalent stress intensity factor (*K*) calculated from J-integral
  - J-integral calculated using numerical volume integration
  - J-integral averaged across wall thickness
  - J-integral approach captures effect of Mode II and III contributions

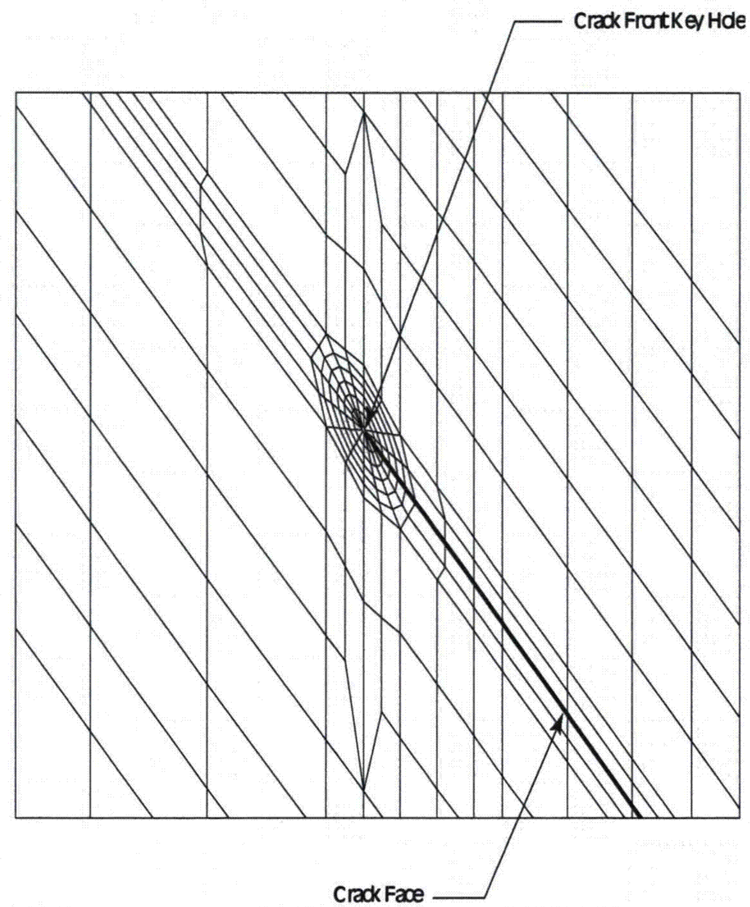
$$K_{eq} = \sqrt{\frac{J_{avg} E}{1-\nu^2}}$$

Fracture Mechanics with WRS Redistribution

Fracture Mechanics Model for Circ Crack in CRDM Nozzle



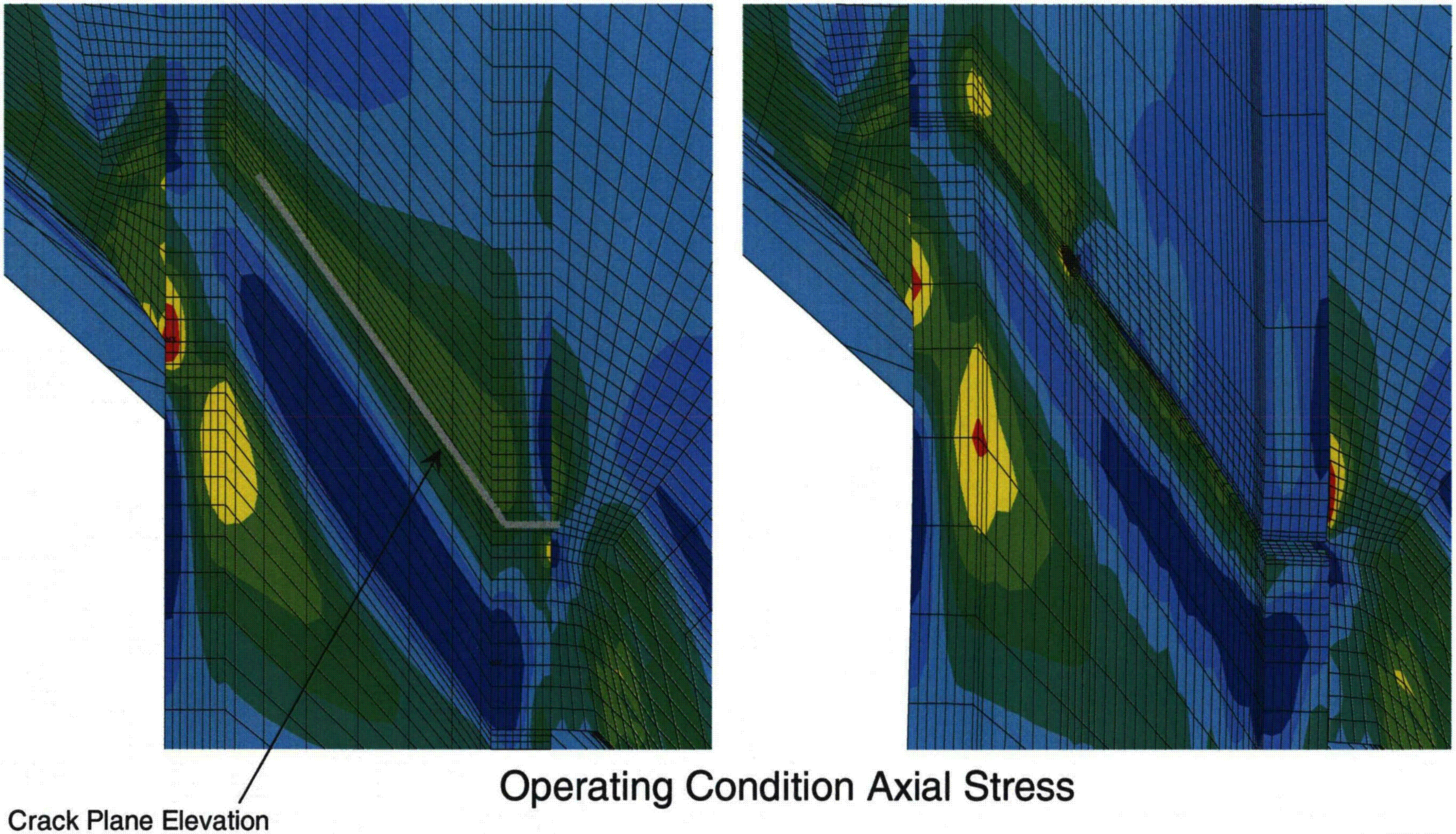
180° Downhill-Centered Crack



Crack Mesh Detail

Fracture Mechanics with WRS Redistribution

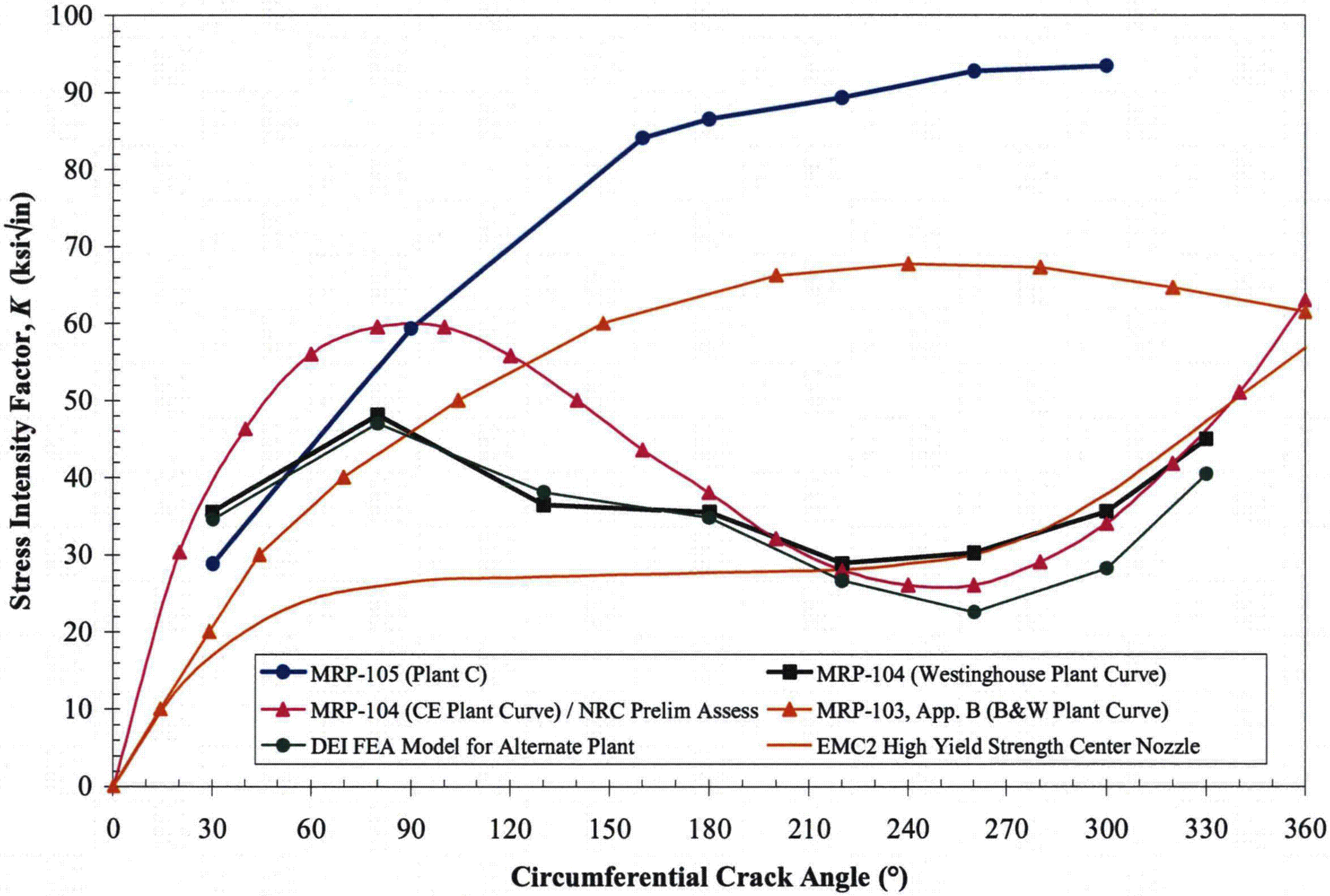
Relief of Axial Stress with Growth of Circ Crack in CRDM Nozzle



Operating Condition Axial Stress

Fracture Mechanics with WRS Redistribution

Comparison to Other Data for Downhill-Centered Circ Crack in CRDM Nozzle

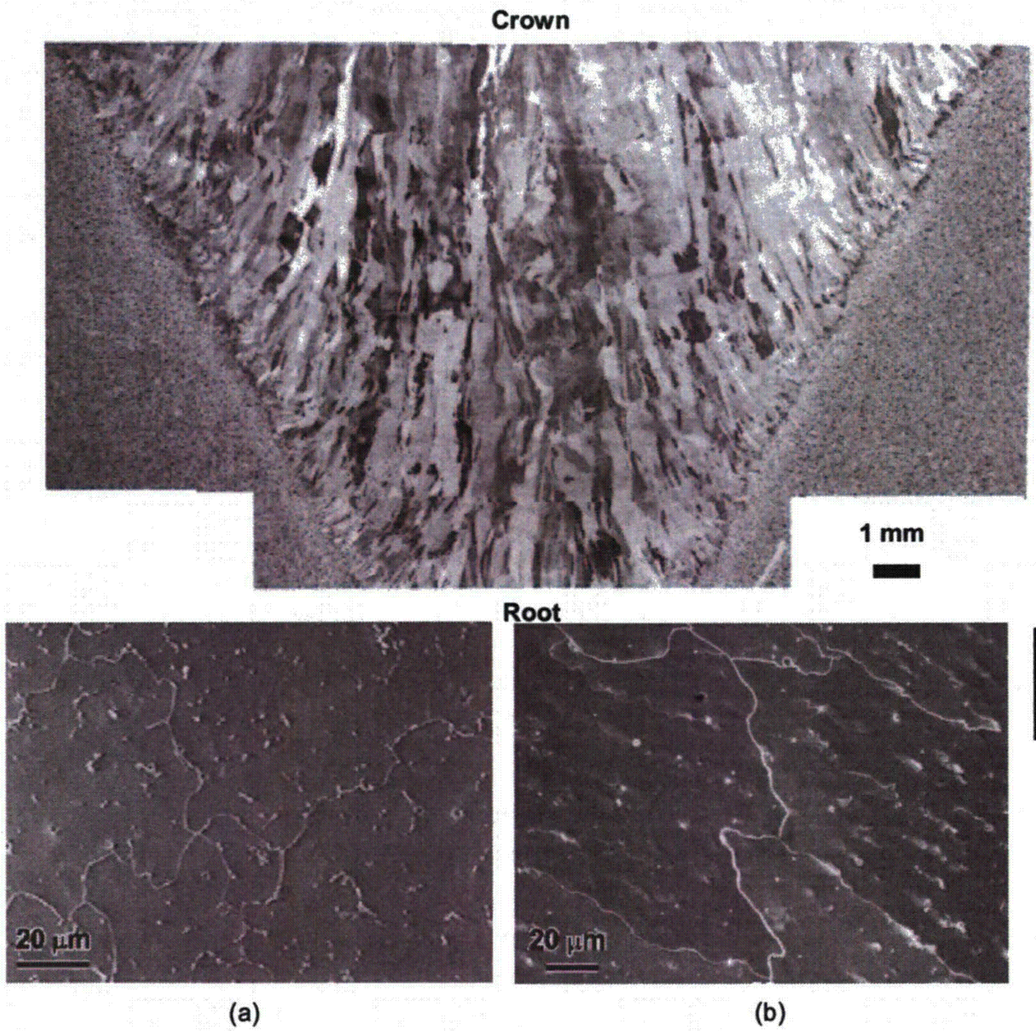


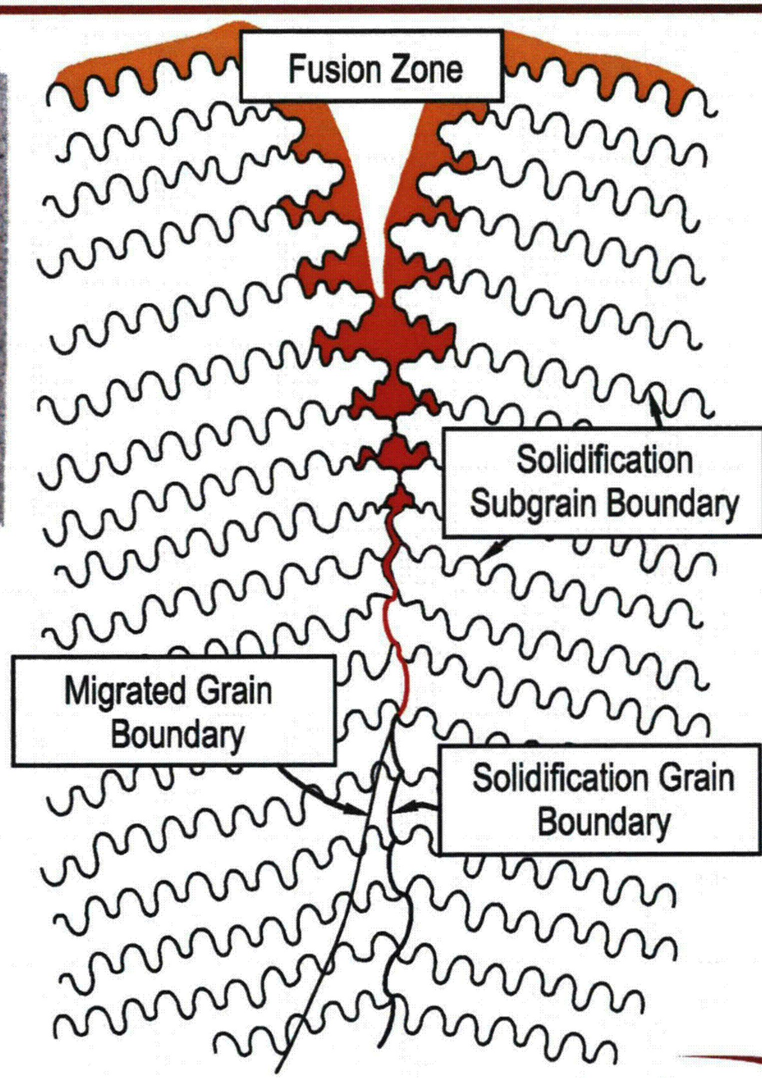
Background
MRP-115 Crack Growth Rate Equation

- With the support of an international expert panel, EPRI developed the MRP-115 report on PWSCC crack growth rates for Alloy 82 and 182 weld materials
  - MRP-115 (EPRI 1006696) was published in proprietary form in 2004, with a non-proprietary version released in 2005
  - The results of MRP-115 were presented at the 2005 EPRI Workshop on Alloy 600 in New Mexico
  - A detailed technical paper covering this study was presented at the *12th International Symposium on Environmental Degradation of Materials in Nuclear Power Systems* (Salt Lake City in August 2005)

MRP-115 Crack Growth Rate Equation

Metallurgical Factors Specific to Weld Metals:
"Cast" Structures are Heterogeneous & Complex

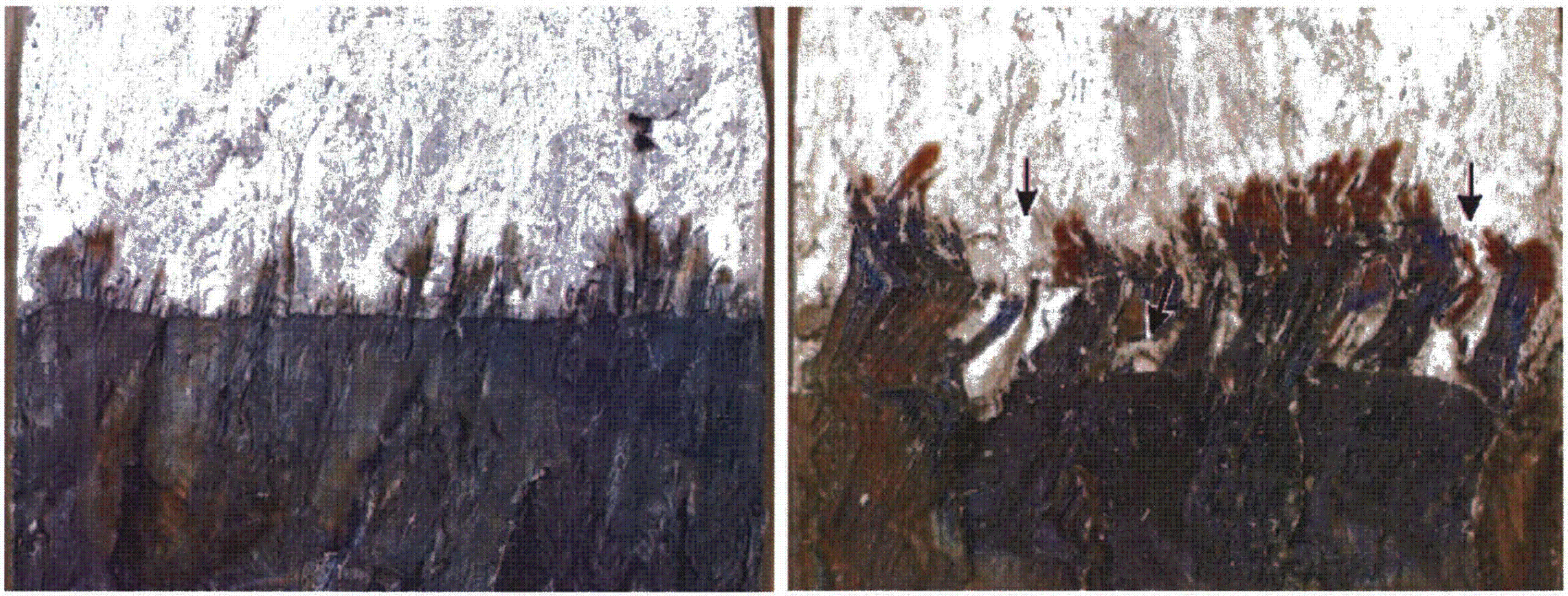




MRP-115 Crack Growth Rate Equation

Metallurgical Factors Specific to Weld Metals: Crack Fronts May Be Highly Irregular (in 2 & 3D)

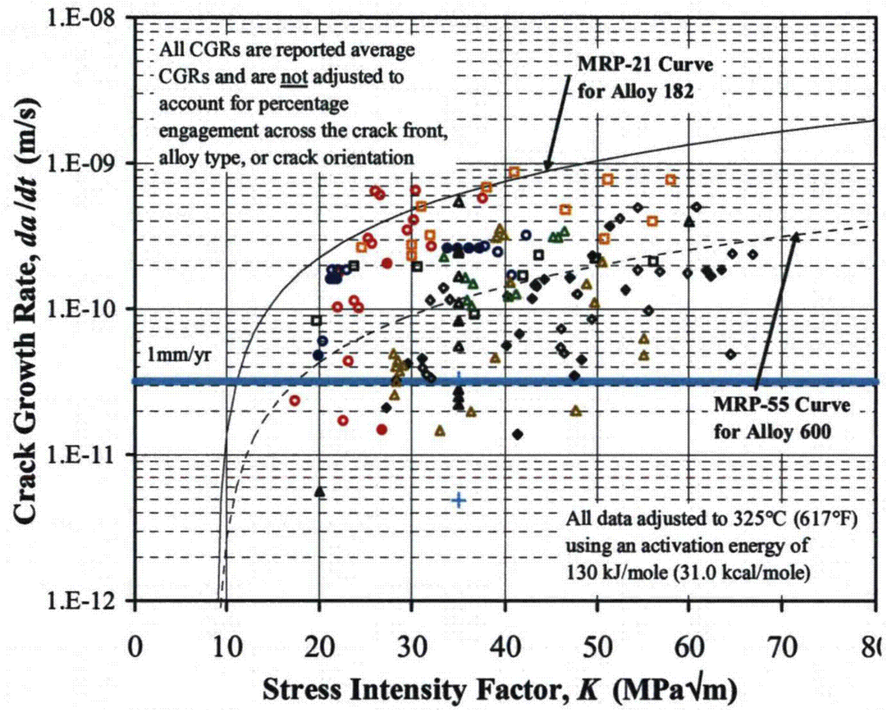
Examples of PWSCC fracture surfaces in Alloy 82 weld metal compact tension (CT) specimens: unclear to what extent patterns arise from fundamental differences in dendritic grain boundary (GB) susceptibility or from failure to transition adequately from the transgranular fatigue pre-crack in air (lack of “engagement”). The latter would be a test artifact of little relevance to field behavior.



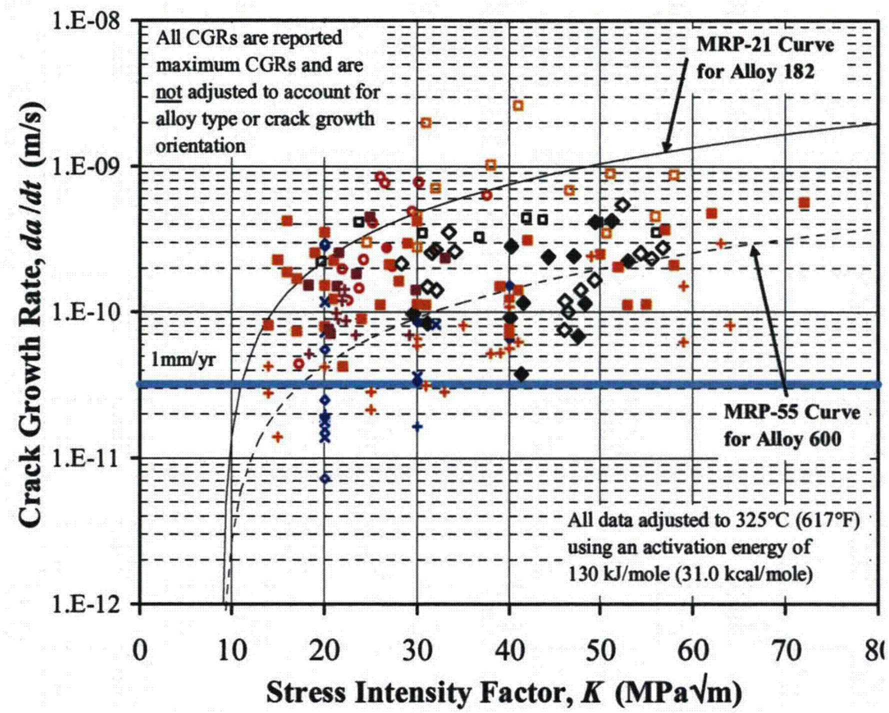
However, recent investigations appear to provide convincing evidence that weld defects (e.g. hot cracking) do NOT play a significant role in PWSCC initiation and propagation.

MRP-115 Crack Growth Rate Equation

Unscreened MRP Lab CGR Database for Alloys 82/182/132



Complete worldwide results for AVERAGE CGR (144 points)



Complete worldwide results for MAXIMUM CGR (158 points)

Decision was made to use average CGR data (as in MRP-55 for Alloy 600)

MRP-115 Crack Growth Rate Equation

Summary

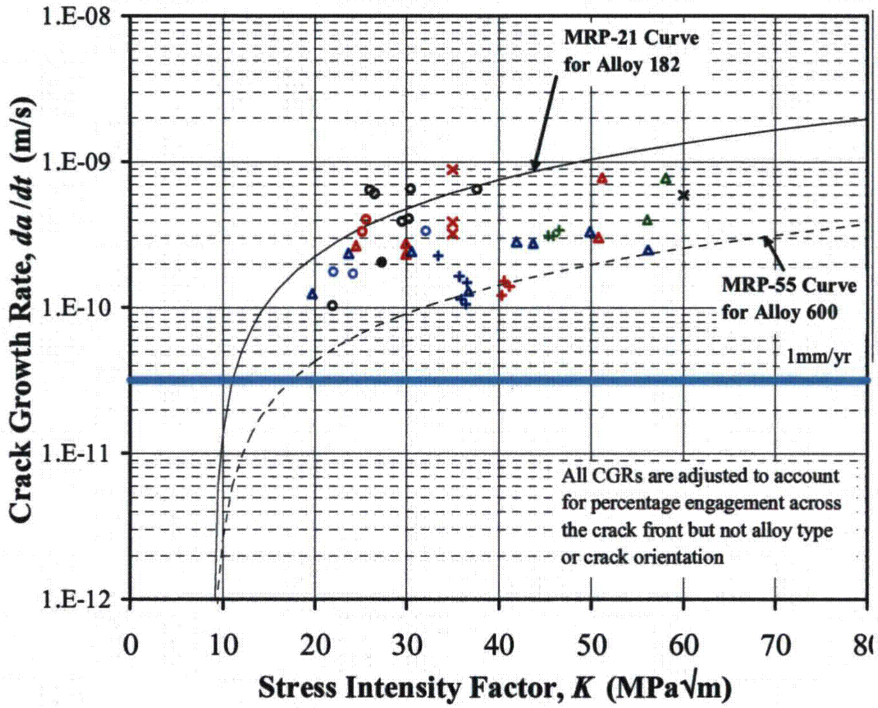
- An international expert panel was formed, collected data, developed data screening criteria, supported development of data reduction processes, and made best practices recommendations for future testing
- For the weld metals, in particular, a methodology was developed for considering the potentially non-conservative effect of incomplete "engagement" to intergranular SCC across the specimen width and over test duration. The approach is appropriate regardless of whether the incomplete engagement:
  - is caused by isolated islands of more crack-resistant material, or
  - is a testing artifact due to the difficulty of the crack transitioning from the transgranular fatigue pre-crack to the intergranular stress corrosion crack
- A stress intensity factor threshold (K_{ISCC}) value was:
  - assumed at 9 MPa$\sqrt{m}$ as a curve-fitting parameter for the Alloy 600 base metal on the basis of crack arrest data for field cracks in Alloy 600 steam generator tubes
  - not assumed at all (i.e. $K_{ISCC} = 0$) for the Alloy 82/182/132 weld metals, based on lack of data and other considerations

MRP-115 Crack Growth Rate Equation
Summary (cont'd)

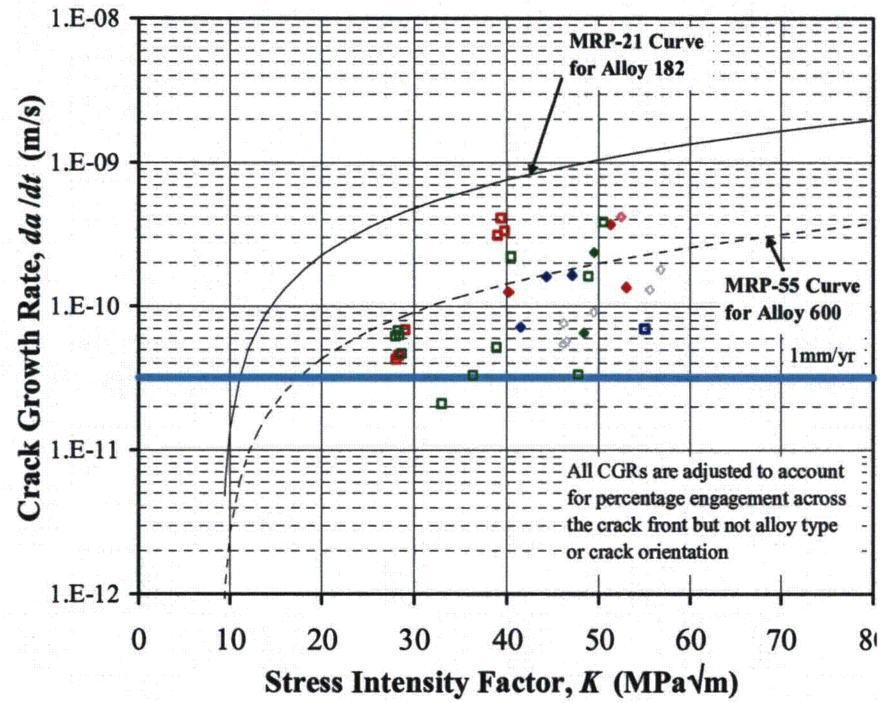
- Linearized, multiple regression statistical models were fitted to the screened databases for Alloy 600 and for Alloy 82/182/132, including:
  - Arrhenius temperature correction
  - Alloy factor (Alloy 182/132 or Alloy 82) for the weld metals
  - Crack orientation factor for the weld metals
  - Crack tip stress intensity factor exponent
    - Assumed 1.16 value for Alloy 600 based on Scott's work with Alloy 600 steam generator tubes
    - Best-fit value of 1.6 for the weld metals derived from the MRP screened laboratory database for Alloy 82/182/132
  - A "heat" or "weld" factor that accounts for the randomness associated with composition, material processing, and weld fabrication
- Insufficient data were available to include dissolved hydrogen concentration (i.e., electrochemical potential), cold work, post-weld heat treatment stress relief, or loading type (constant or periodic unloading) directly in the models

MRP-115 Crack Growth Rate Equation

Screened MRP Lab CGR Database for Alloys 82/182/132



Average CGR data for Alloys 182/132 after screening (43 points)

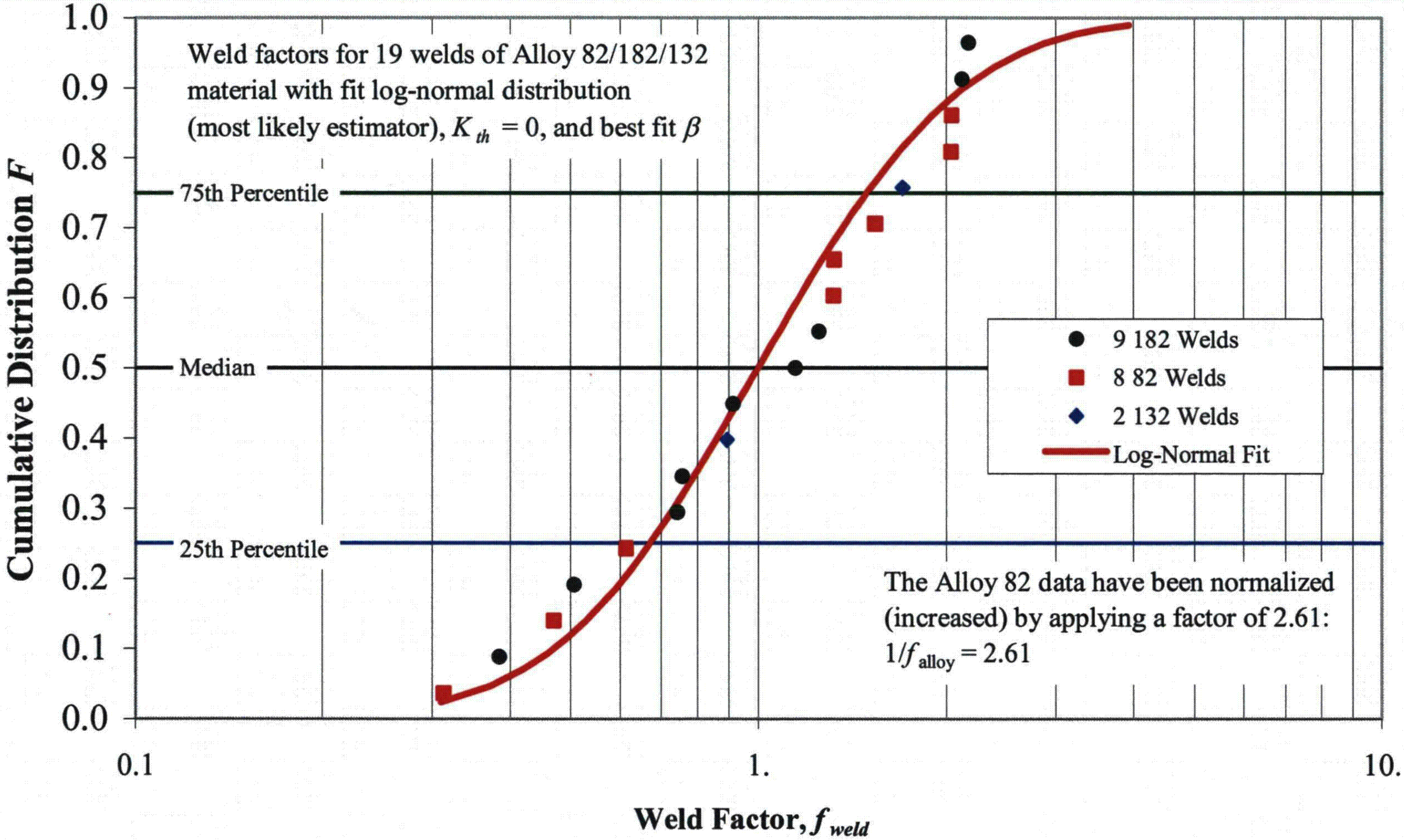


Average CGR data for Alloy 82 after screening (34 points)

Note the absence of results at K-values < 20 (A182) & < 28 MPa√m (A82)

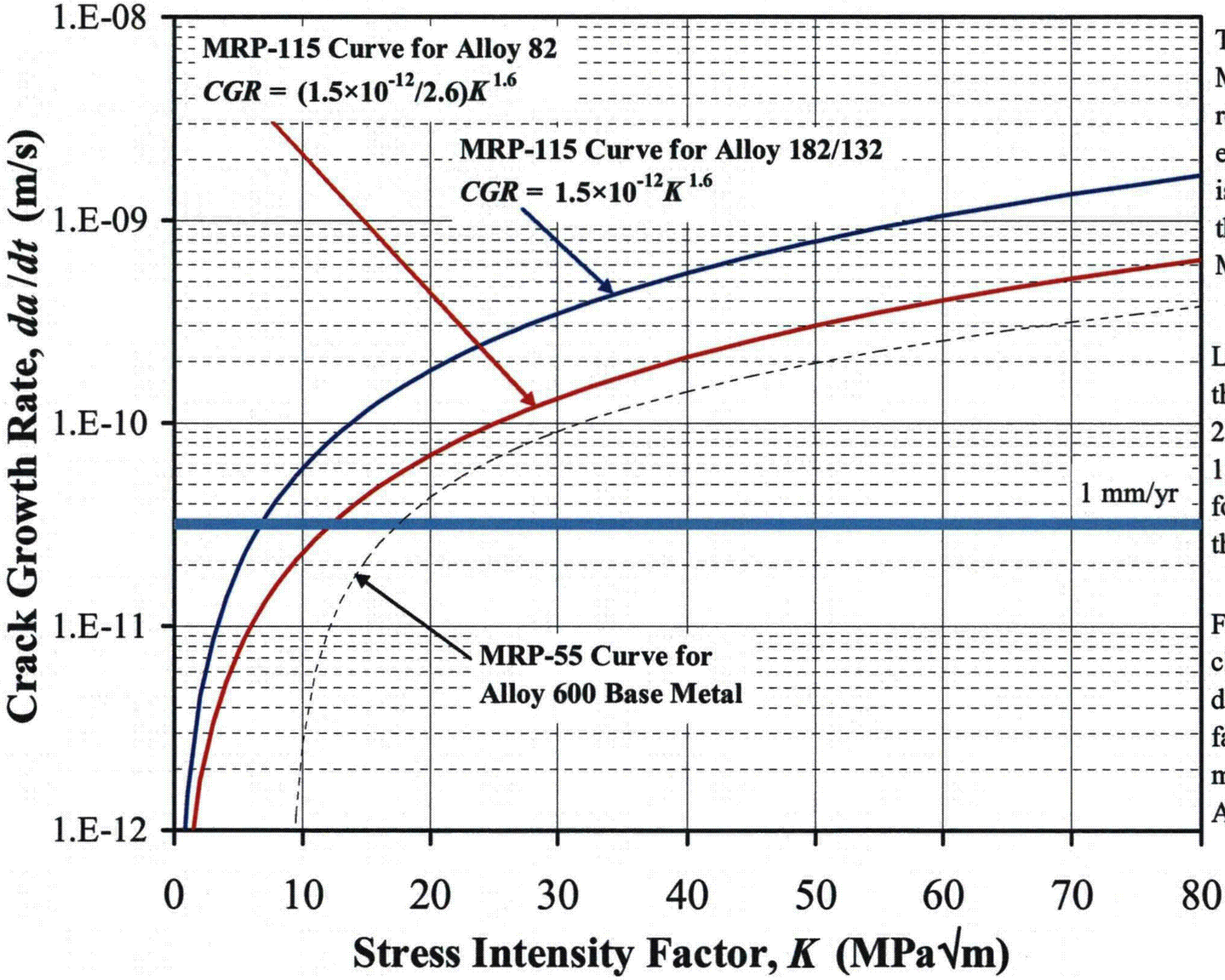
MRP-115 Crack Growth Rate Equation

Distribution of Screened Data by "Weld Factor"



MRP-115 Crack Growth Rate Equation

Recommended Disposition Curves (325°C)



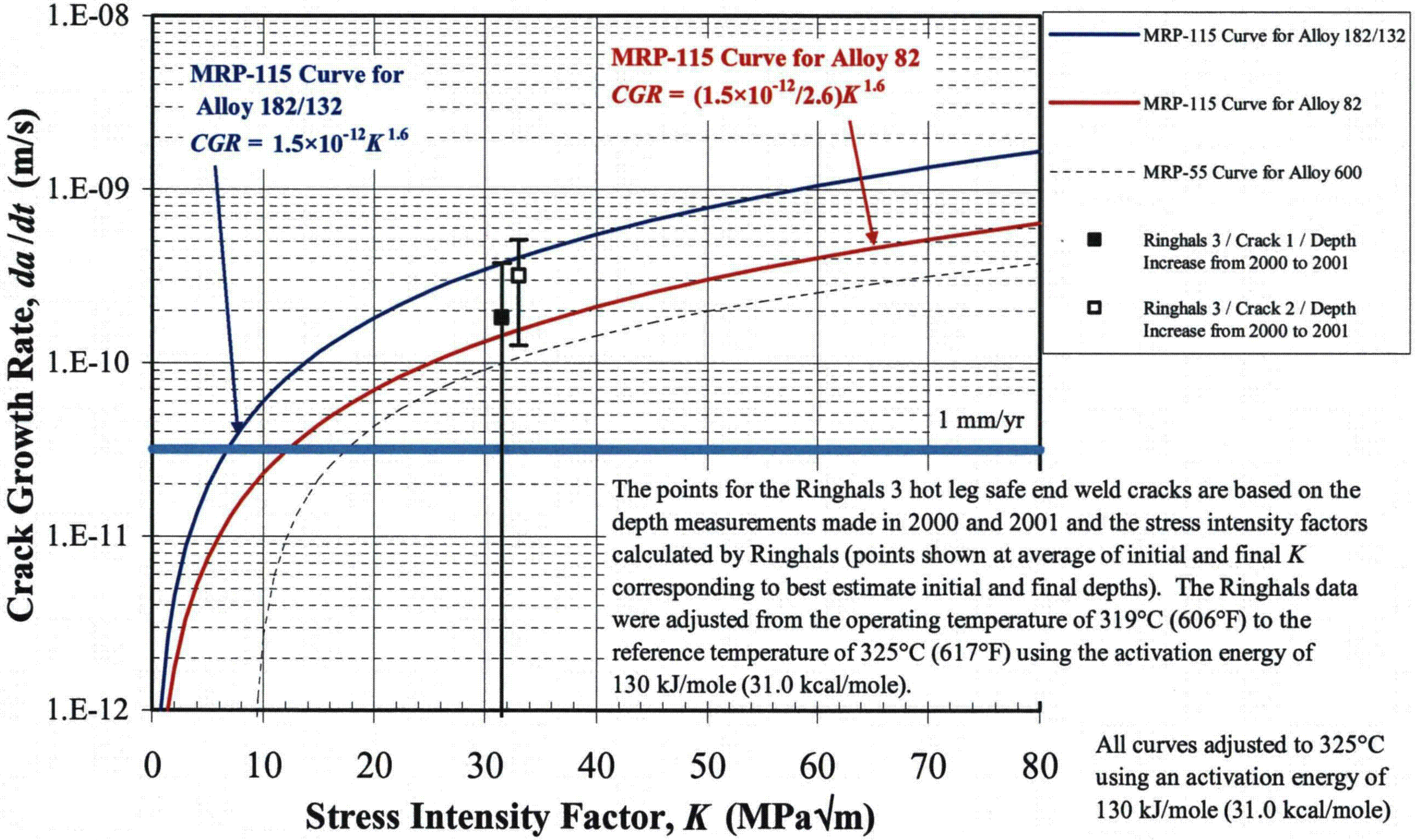
The reference temperature for the MRP curves is 325°C (617°F); the recommended thermal activation energy for temperature adjustment is 130 kJ/mole (31.0 kcal/mole), the same value recommended in MRP-55 for base metal.

Laboratory testing indicates that the CGR for Alloy 82 is on average 2.6 times lower than that for Alloy 182/132, so the MRP-115 curve for Alloy 82 is 2.6 times lower than the curve for Alloy 182/132.

For crack propagation that is clearly perpendicular to the dendrite solidification direction, a factor of 2.0 lowering the CGR may be applied to the curves for Alloy 182 (or 132) and Alloy 82.

MRP-115 Crack Growth Rate Equation

Comparison with Ringhals Plant Inspection Data



The points for the Ringhals 3 hot leg safe end weld cracks are based on the depth measurements made in 2000 and 2001 and the stress intensity factors calculated by Ringhals (points shown at average of initial and final K corresponding to best estimate initial and final depths). The Ringhals data were adjusted from the operating temperature of 319°C (606°F) to the reference temperature of 325°C (617°F) using the activation energy of 130 kJ/mole (31.0 kcal/mole).

All curves adjusted to 325°C using an activation energy of 130 kJ/mole (31.0 kcal/mole)

White Paper Section 5 Calculation

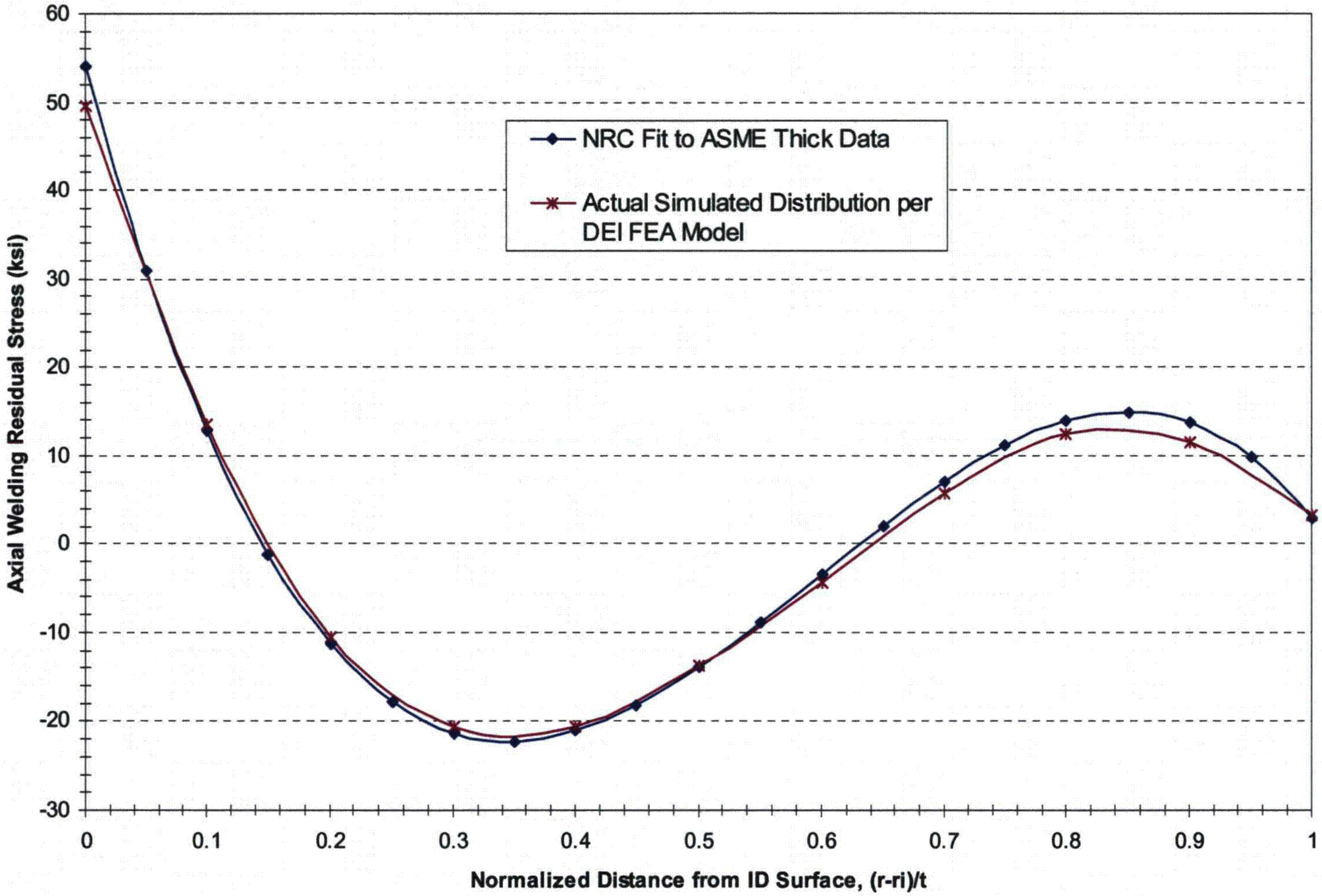
- The approach to the DEI calculation presented in Section 5 of the White Paper was largely identical to the approach of the NRC calculation presented on November 30:
  - Wolf Creek relief nozzle weld OD and wall thickness as assumed in NRC calculation
  - Same treatment of relief nozzle pipe loads for crack growth as assumed in NRC calculation (deadweight, pressure, pipe thermal expansion reported for relief nozzle)
  - Assumption of same relief nozzle welding residual stress (WRS) profile (54 ksi on ID) as for NRC calculation
  - Use of deterministic MRP-115 crack growth equation for Alloy 182 weld material
  - Same treatment of pipe loads in critical crack size calculation (deadweight, pressure, pipe thermal expansion for normal operation; plus SSE for faulted)
  - Identical assumption of initial crack aspect ratio (21:1) and depth (26%tw)
  - Crack growth driven by stress intensity factor at deepest and surface points on crack front, with shape maintained as a semi-ellipse

White Paper Section 5 Calculation (cont'd)

- The following refinements were made:
  - Consideration of possible effect of residual stress relaxation with crack growth
  - FEA stress intensity factor calculations to remove uncertainties associated with extrapolation of published solutions to D/t ratio of Wolf Creek relief nozzle and to relatively large crack length-to-depth aspect ratios (c/a)
- Under these assumptions, the DEI calculation showed:
  - longer time to through-wall penetration and rupture (4.4 years)
  - similar behavior with regard to time between through-wall penetration and leakage
- Scoping calculations performed subsequent to the December 20 public NRC meeting indicates that the assumption of crack growth driven by the stress intensity factor at the deepest and surface points resulted in overly conservative results with regard to the time between leakage and rupture

White Paper Section 5 Calculation

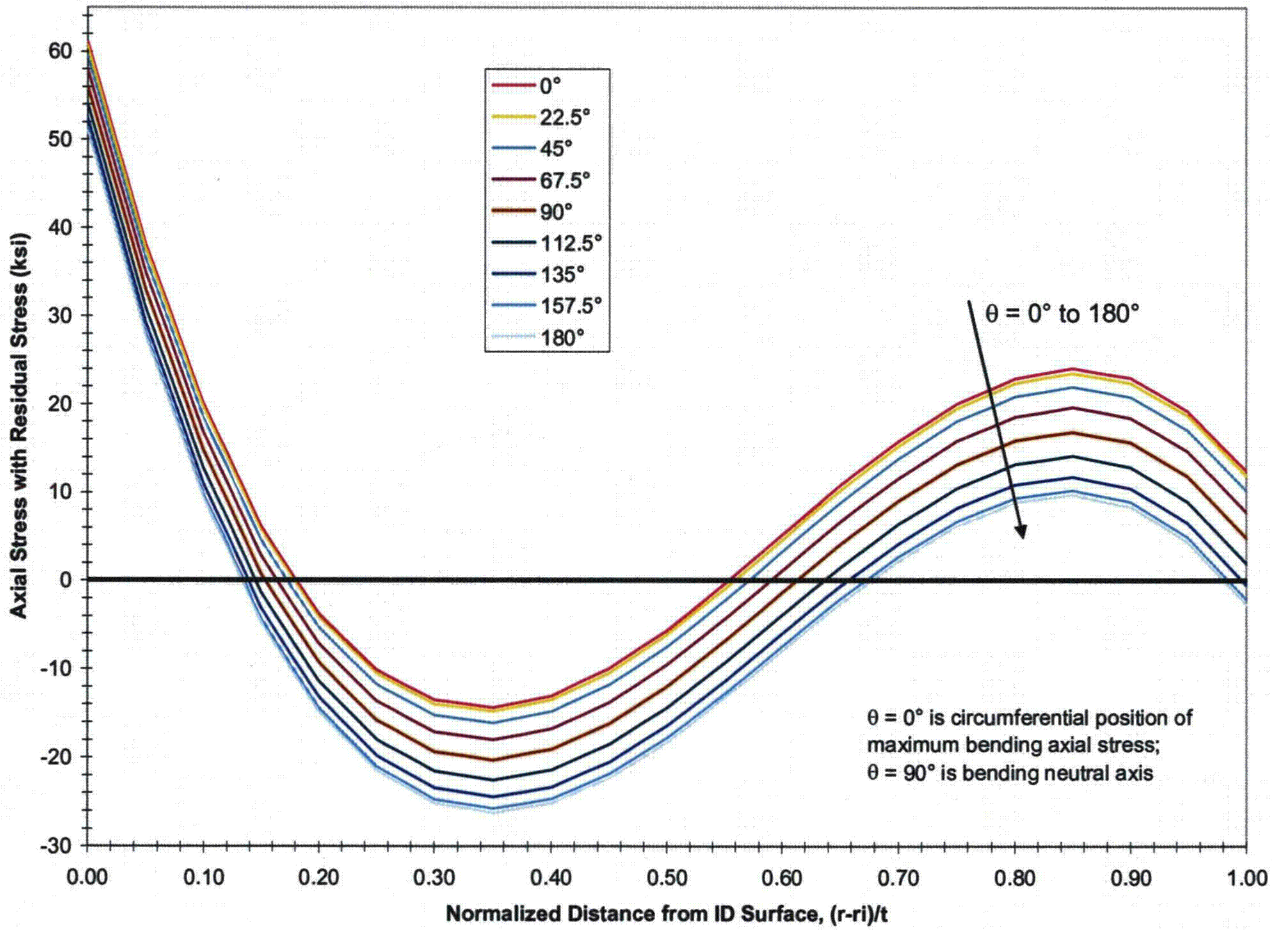
WRS Distribution Assumption Based on ASME Data



White Paper Section 5 Calculation

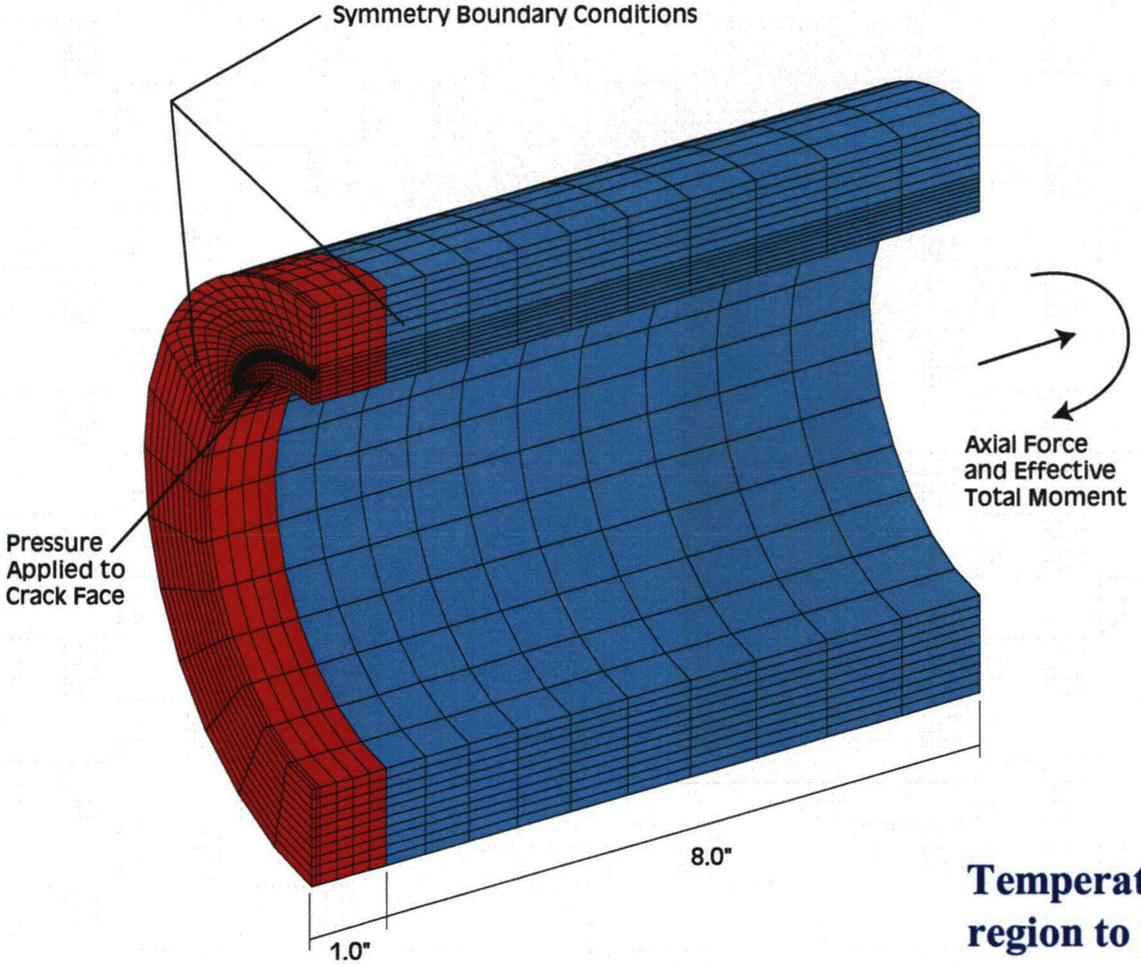
Assumed Axial Stress Loading for Crack Growth

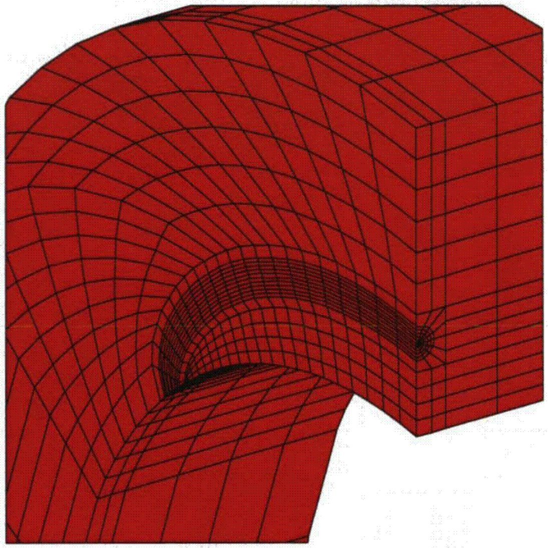
- Deadweight
- Pipe Thermal Expansion Force and Moment
- End Cap Pressure Load
- Assumed WRS Distribution



White Paper Section 5 Calculation

FEA Fracture Mechanics Model Using FEACrack / ANSYS

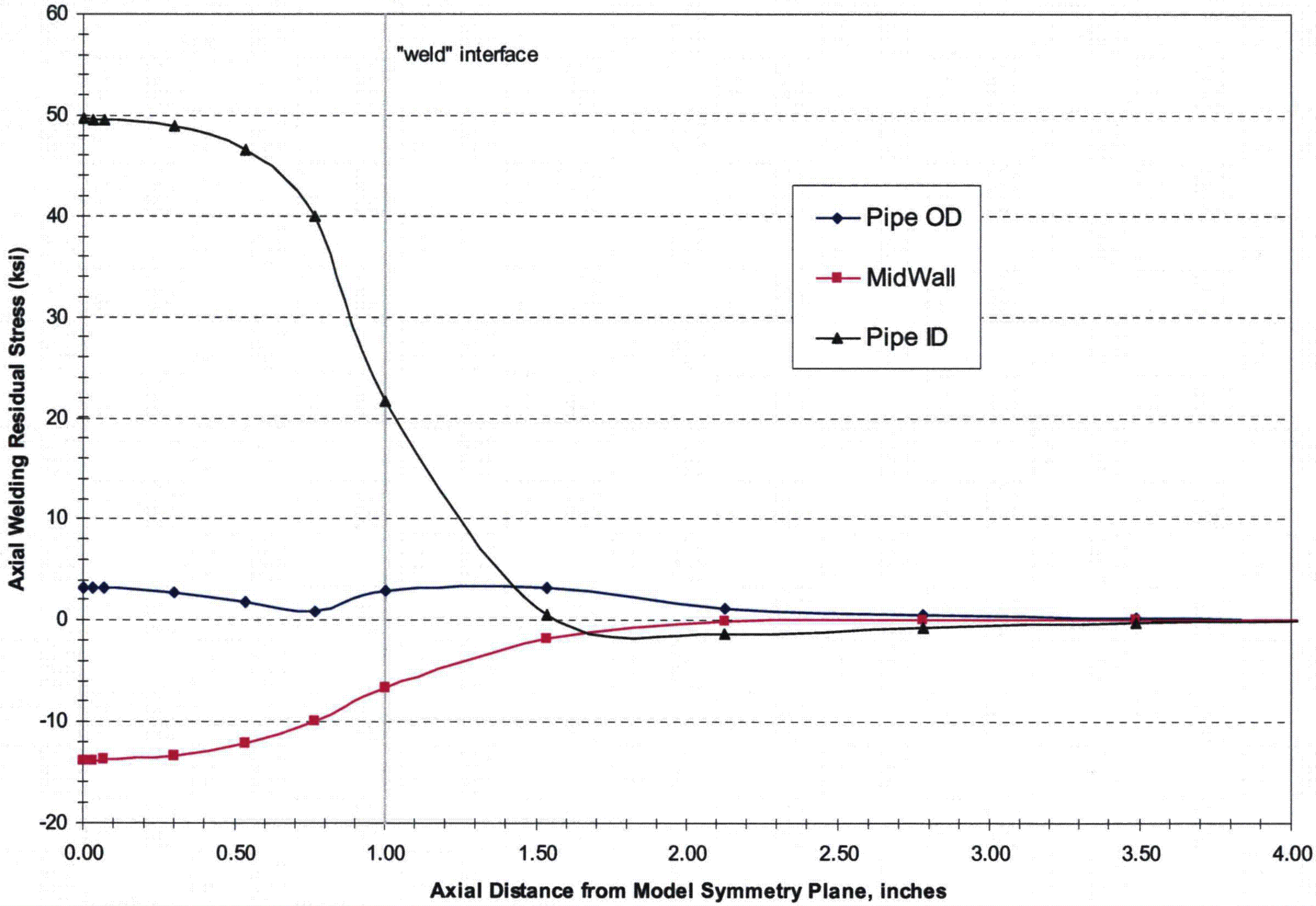




Temperature profile applied to red region to produce WRS profile

White Paper Section 5 Calculation

Axial Extent of Imposed Thermal Stress Simulating WRS



White Paper Section 5 Calculation

Fracture Mechanics Verification and Validation Cases

Inside Diameter Scaled up to Ri/t = 3 for Direct Comparison to Anderson Correlation Based on NRC Assumed WRS Distribution (with Scaled up Loading Resulting in Comparable Axial Stress Distribution)

						Anderson (ksi-in$^{0.5}$)		DEI FEA (ksi-in$^{0.5}$)		Deviation	
No.	crack	Ri/t	a/t	2c/a	2θ (deg)	Ksurf	Kdeep	Ksurf	Kdeep	Ksurf	Kdeep
V1	semi-elliptical	3	0.2	16	61.1	19.8	19.5	28.7	21.1	8.9	1.6
V2	semi-elliptical	3	0.4	16	122.2	24.0	6.7	31.9	9.0	7.8	2.3
V3	semi-elliptical	3	0.6	16	183.3	25.5	10.3	30.8	12.5	5.4	2.1
V4	semi-elliptical	3	0.8	16	244.5	25.0	29.6	27.9	29.9	2.9	0.3

Inside Diameter Scaled up to Ri/t = 3 for Direct Comparison to Anderson Correlation Based on Actual FEA WRS Distribution Attained (with Scaled up Loading Resulting in Comparable Axial Stress Distribution)

						Anderson (ksi-in$^{0.5}$)		DEI FEA (ksi-in$^{0.5}$)		Deviation	
No.	crack	Ri/t	a/t	2c/a	2θ (deg)	Ksurf	Kdeep	Ksurf	Kdeep	Ksurf	Kdeep
V1	semi-elliptical	3	0.2	16	61.1	18.6	18.9	28.7	21.1	10.1	2.2
V2	semi-elliptical	3	0.4	16	122.2	22.6	6.9	31.9	9.0	9.3	2.1
V3	semi-elliptical	3	0.6	16	183.3	23.8	9.5	30.8	12.5	7.0	3.0
V4	semi-elliptical	3	0.8	16	244.5	23.3	26.5	27.9	29.9	4.6	3.4

Selected FEA Cases for Case of No WRS Loading for Comparison to Anderson Correlation Extrapolated Down to Ri/t = 2.004

						Anderson (ksi-in$^{0.5}$)		DEI FEA (ksi-in$^{0.5}$)		Deviation	
No.	crack	Ri/t	a/t	2c/a	2θ (deg)	Ksurf	Kdeep	Ksurf	Kdeep	Ksurf	Kdeep
3	semi-elliptical	2.004	0.1	15	42.9	2.6	6.2	2.9	6.4	0.4	0.2
15	semi-elliptical	2.004	0.3	5	42.9	7.2	9.9	7.8	10.1	0.6	0.2
18	semi-elliptical	2.004	0.3	21	180.1	2.4	12.2	2.3	12.1	-0.1	-0.1
20	semi-elliptical	2.004	0.3	30	257.3	1.5	13.0	0.6	12.2	-0.9	-0.8

White Paper Section 5 Calculation

Matrix of FEA Results for Wolf Creek Relief Nozzle

Matrix of FEA Fracture Mechanics Cases Investigated for Relief Nozzle Dissimilar Metal Weld Dimensions and Loading with Comparison of Results to Anderson Correlation Based on NRC Assumed WRS Distribution Extrapolated Down to Ri/t = 2.004

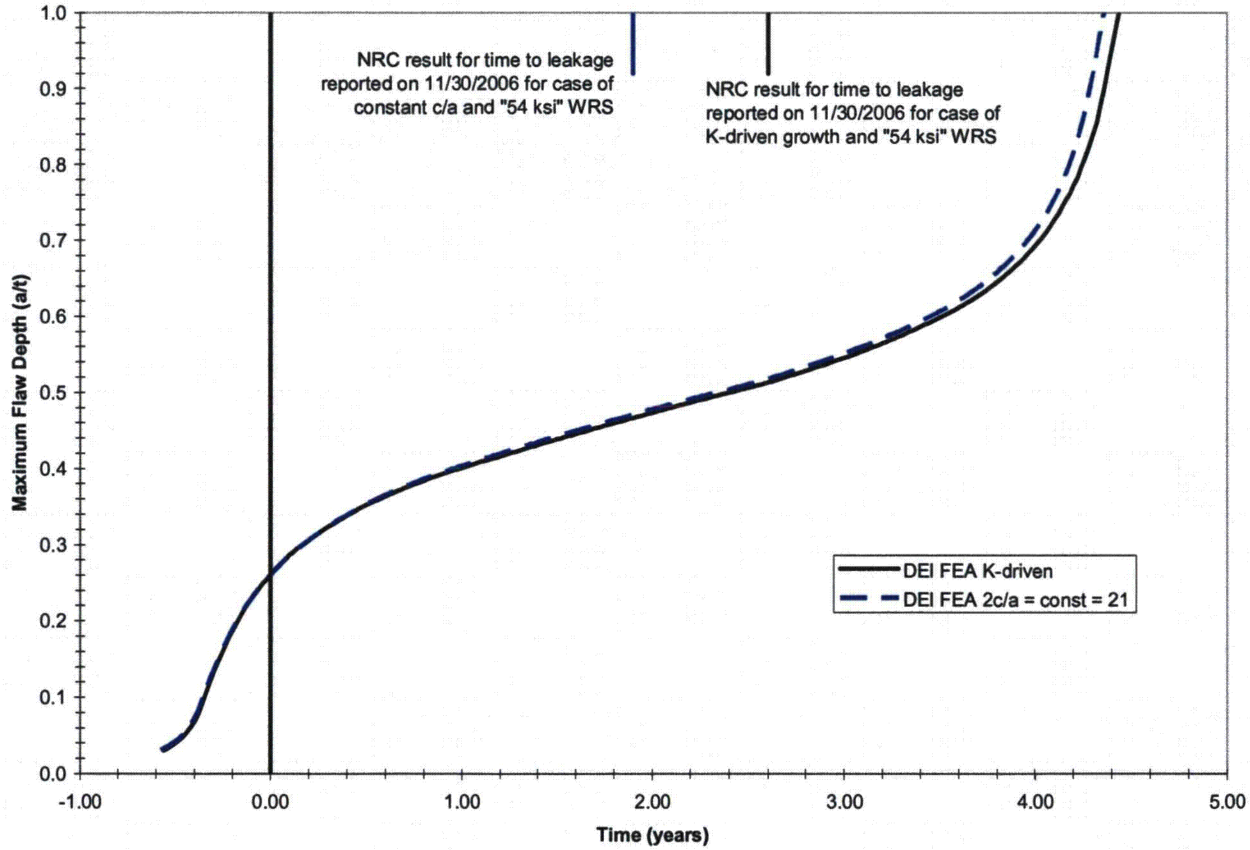
						Anderson (ksi-in$^{0.5}$)		DEI FEA (ksi-in$^{0.5}$)		Deviation	
No.	crack	Ri/t	a/t	2c/a	2θ (deg)	Ksurf	Kdeep	Ksurf	Kdeep	Ksurf	Kdeep
1	semi-elliptical	2.004	0.1	5	14.3	25.2	20.8	31.0	22.4	5.9	1.6
2	semi-elliptical	2.004	0.1	10	28.6	20.7	23.7	24.9	25.7	4.2	2.0
3	semi-elliptical	2.004	0.1	15	42.9	16.1	24.2	22.3	26.7	6.2	2.5
4	semi-elliptical	2.004	0.1	21	60.0	13.5	24.8	19.8	27.3	6.4	2.5
5	semi-elliptical	2.004	0.1	25	71.5	12.1	25.2	19.3	27.4	7.3	2.1
6	semi-elliptical	2.004	0.1	30	85.8	10.3	25.7	18.1	27.5	7.9	1.8
7	semi-elliptical	2.004	0.1	50	143.0			15.3	27.8		
8	semi-elliptical	2.004	0.2	5	28.6	32.1	14.1	38.2	15.3	6.1	1.2
9	semi-elliptical	2.004	0.2	10	57.2	26.6	17.1	32.1	18.5	5.5	1.4
10	semi-elliptical	2.004	0.2	15	85.8	20.9	18.0	28.4	19.5	7.4	1.5
11	semi-elliptical	2.004	0.2	21	120.1	17.7	19.0	25.4	20.1	7.7	1.1
12	semi-elliptical	2.004	0.2	25	143.0	16.0	19.7	23.5	20.3	7.5	0.6
13	semi-elliptical	2.004	0.2	30	171.6	13.8	20.5	22.4	20.5	8.6	0.0
14	semi-elliptical	2.004	0.2	50	285.9			22.3	20.5		
15	semi-elliptical	2.004	0.3	5	42.9	35.5	6.0	41.2	7.9	5.7	1.9
16	semi-elliptical	2.004	0.3	10	85.8	29.4	8.6	34.9	10.5	5.5	1.9
17	semi-elliptical	2.004	0.3	15	128.7	23.1	9.7	30.7	11.4	7.7	1.7
18	semi-elliptical	2.004	0.3	21	180.1	19.7	10.9	27.3	11.9	7.5	1.0
19	semi-elliptical	2.004	0.3	25	214.4	18.1	11.7	25.4	12.1	7.3	0.4
20	semi-elliptical	2.004	0.3	30	257.3	16.0	12.6	23.8	12.2	7.8	-0.3
21	semi-elliptical	2.004	0.4	10	114.4	30.6	3.1	35.7	5.8	5.0	2.7
22	semi-elliptical	2.004	0.4	15	171.6	23.5	4.2	31.1	6.6	7.5	2.4
23	semi-elliptical	2.004	0.4	21	240.2	20.5	5.4	27.3	6.9	6.9	1.6
24	semi-elliptical	2.004	0.4	25	285.9	19.1	6.1	25.4	7.0	6.3	0.9
25	semi-elliptical	2.004	0.4	30	343.1	17.5	7.0	23.6	7.0	6.1	0.0
26	semi-elliptical	2.004	0.5	24	343.1	19.7	4.4	25.7	6.0	6.0	1.7
27	semi-elliptical	2.004	0.6	20	343.1	21.2	7.5	27.2	9.2	6.0	1.7
28	semi-elliptical	2.004	0.7	10	200.1	30.9	14.3	33.0	15.6	2.1	1.3
29	semi-elliptical	2.004	0.7	17.14	343.1	21.6	15.2	27.9	16.1	6.3	0.9
30	semi-elliptical	2.004	0.8	10	228.7	29.2	24.6	31.5	25.0	2.3	0.4
31	semi-elliptical	2.004	0.8	15	343.1	22.5	25.6	28.5	25.9	6.0	0.3
32	semi-elliptical	2.004	0.9	10	257.3	27.7	34.7	29.8	38.3	2.1	3.6
33	semi-elliptical	2.004	0.9	13.33	343.1	23.3	35.9	28.8	39.9	5.5	4.0
34	uniform depth	2.004	0.7	17.49	350.0			0.0*	16.5		
35	uniform depth	2.004	0.8	15.30	350.0			0.0*	26.9		
36	uniform depth	2.004	0.9	13.60	350.0			1.3*	42.5		

*The Ksurf values for the uniform depth crack geometry are for a position 150° from the point of max bending stress. The two zero values for Ksurf represent crack tip closing at the 150° location.

White Paper Section 5 Calculation

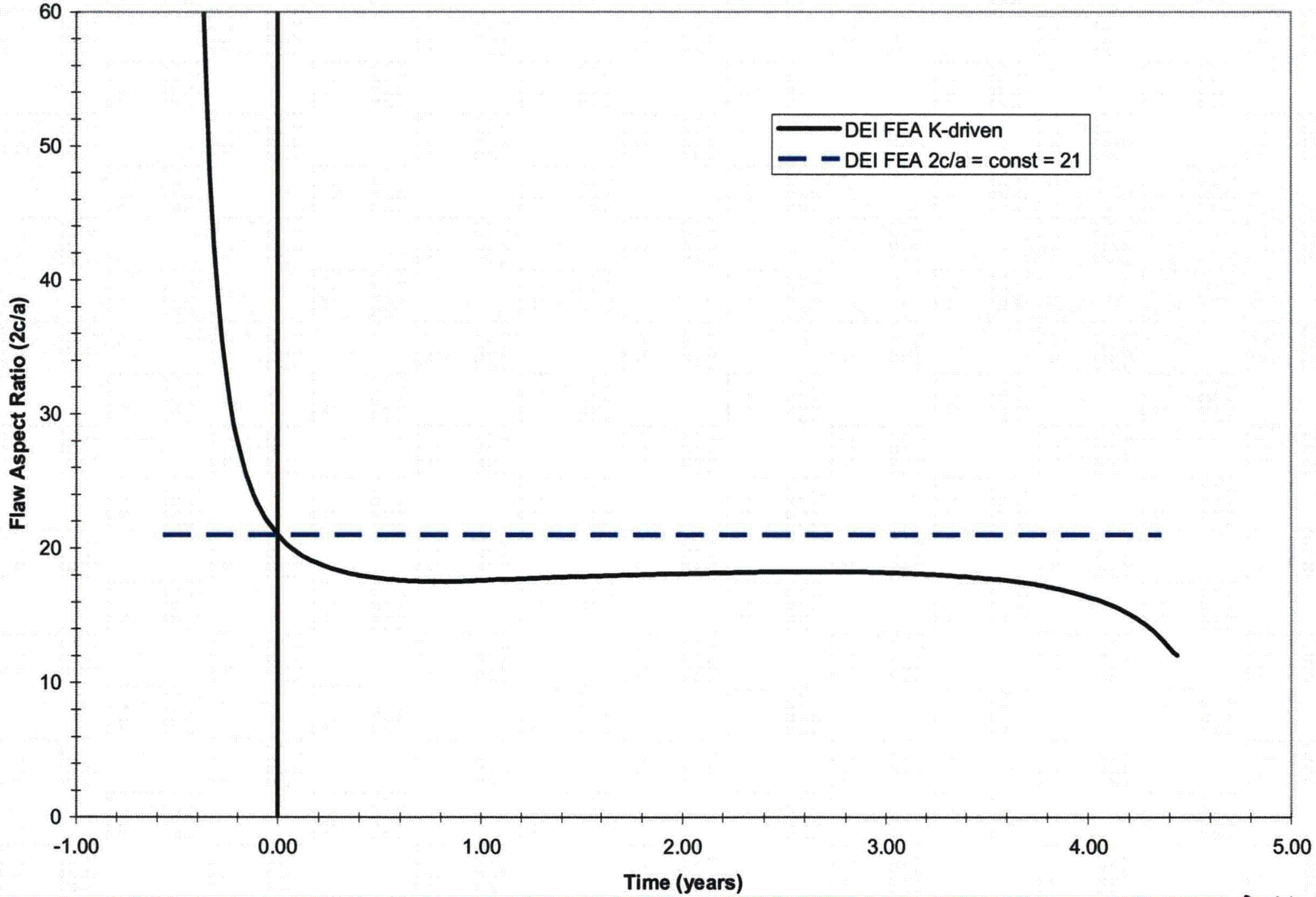
Predicted Growth in Depth Direction

- Crack Development Based on
  - Initial length-to-depth aspect ratio of 21:1 based on NDE
  - Interpolation in FEA SIF results for deepest and surface points
  - Semi-elliptical crack shape
  - MRP-115 crack growth rate equation for Alloy 182



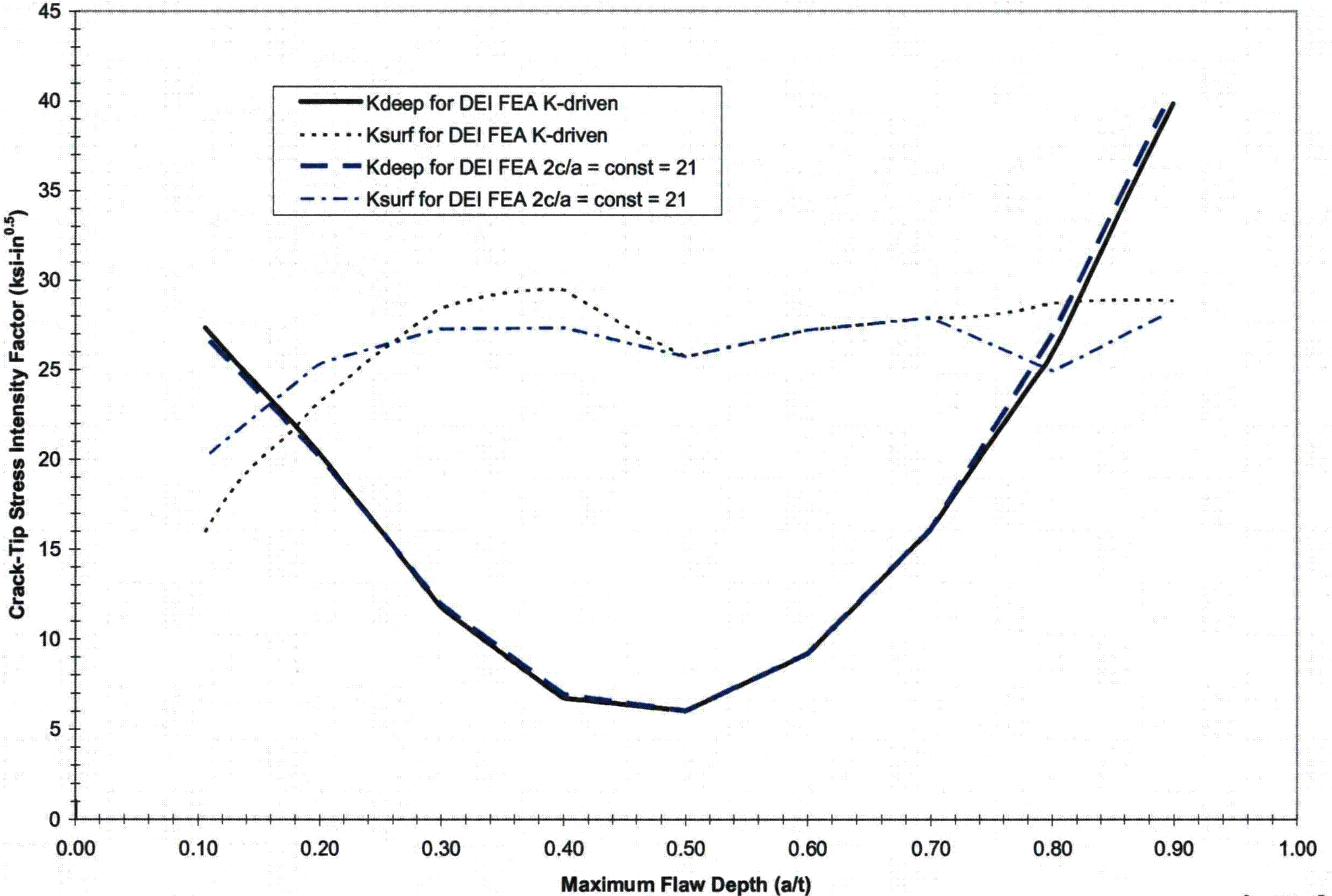
White Paper Section 5 Calculation

Predicted Aspect Ratio Development



White Paper Section 5 Calculation

SIFs from FEA Case Interpolation

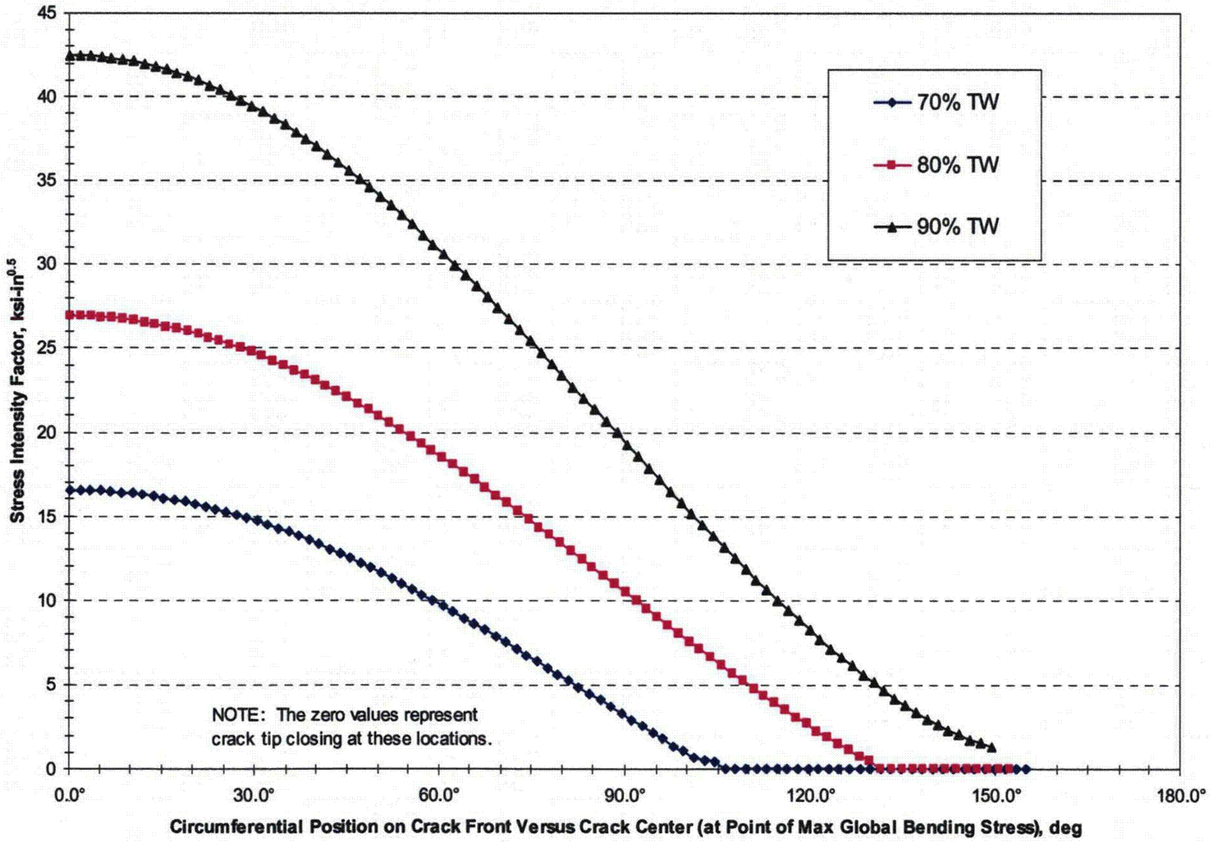


Dominion Engineering, Inc.

White Paper Section 5 Calculation

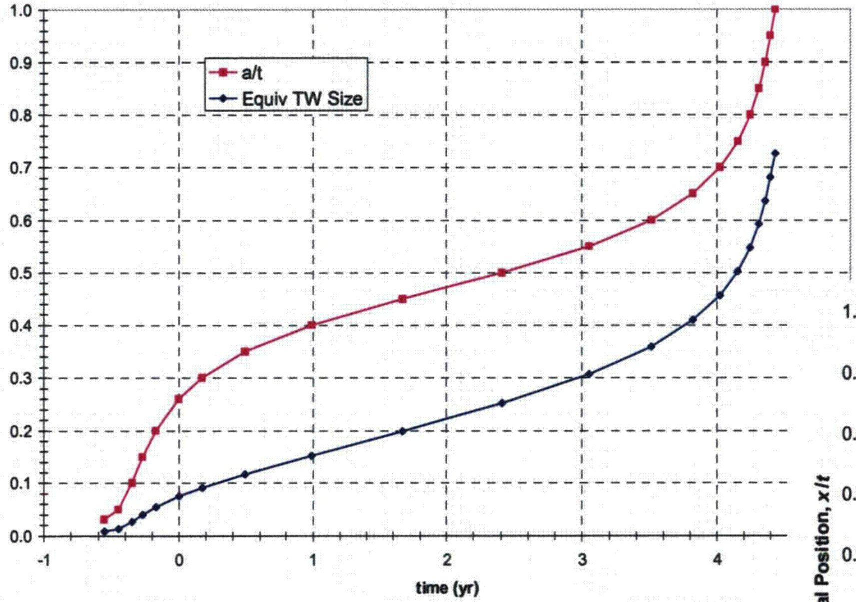
SIF around Crack Front for Uniform Depth Crack (350° Length)

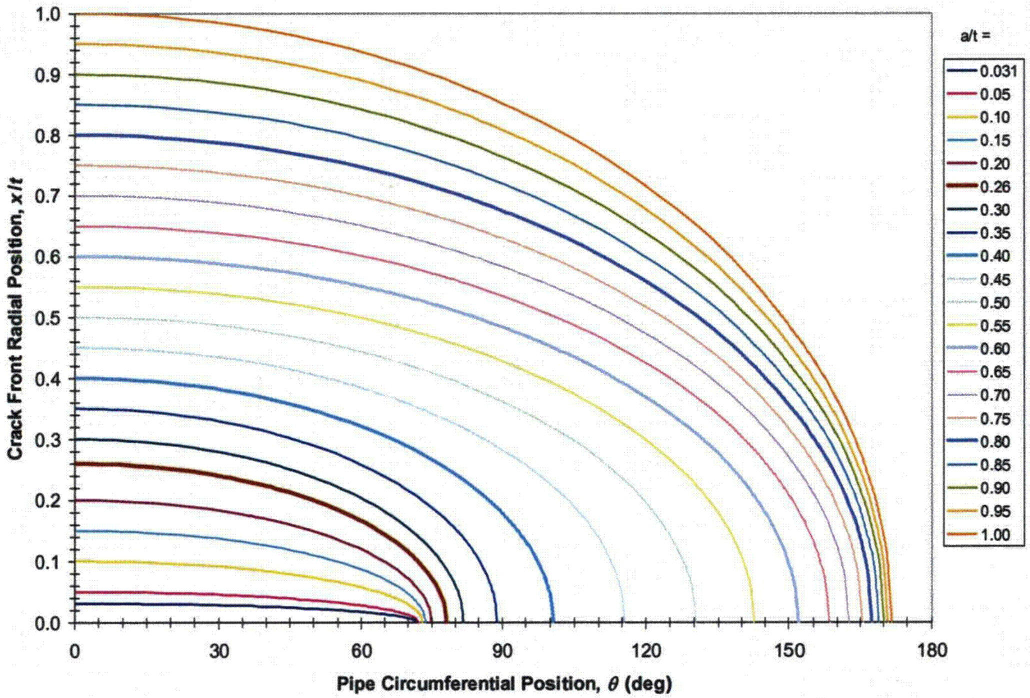
- Zero values of SIF correspond to crack tip closure, implying crack arrest on compressive side of neutral axis



White Paper Section 5 Calculation

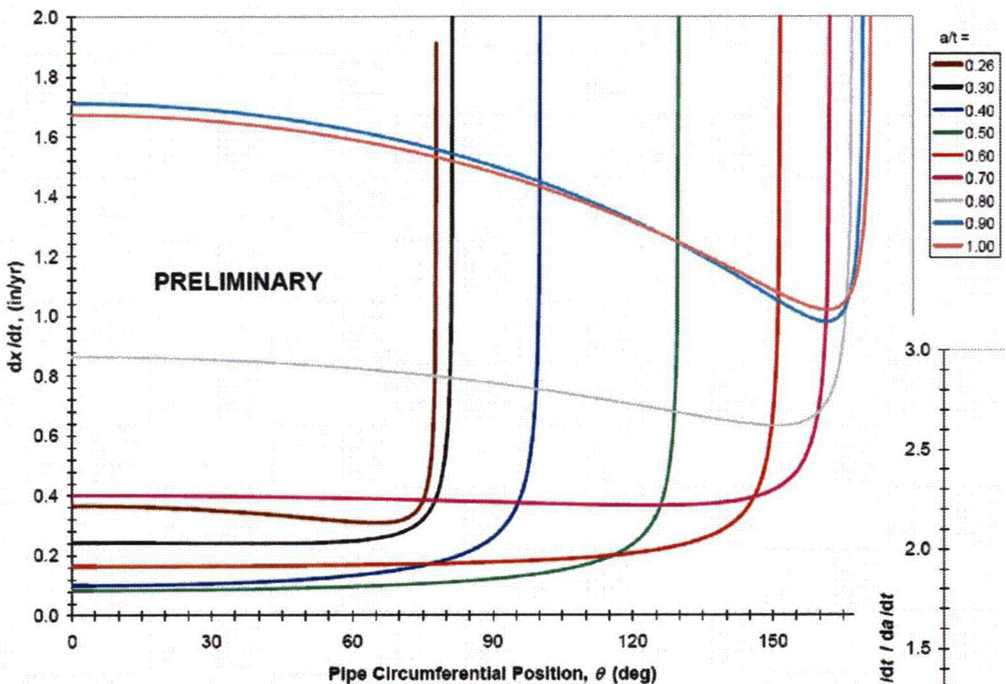
Supplemental Interpretation of Results:
Crack Aspect Ratio Development

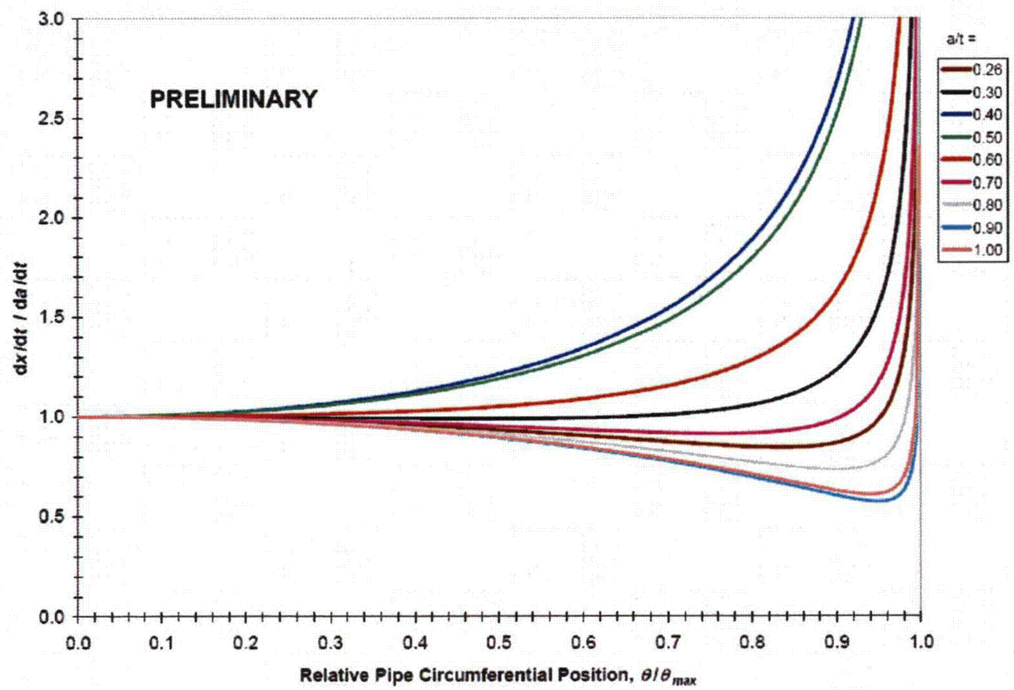




White Paper Section 5 Calculation

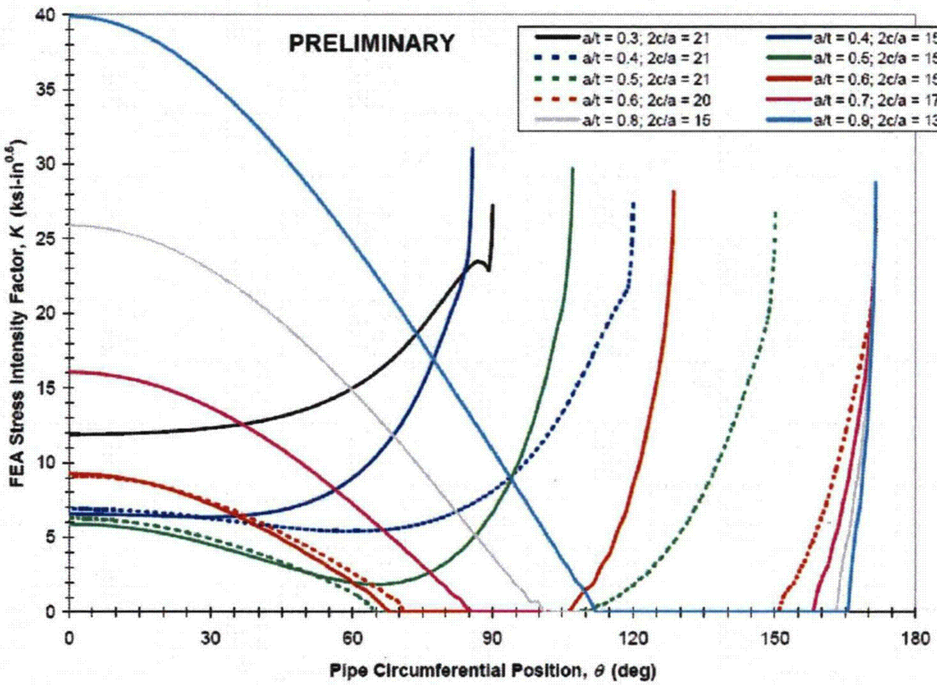
Supplemental Interpretation of Results:
Radial Rate of Movement of Crack Front (dx/dt) for Semi-elliptical Shape

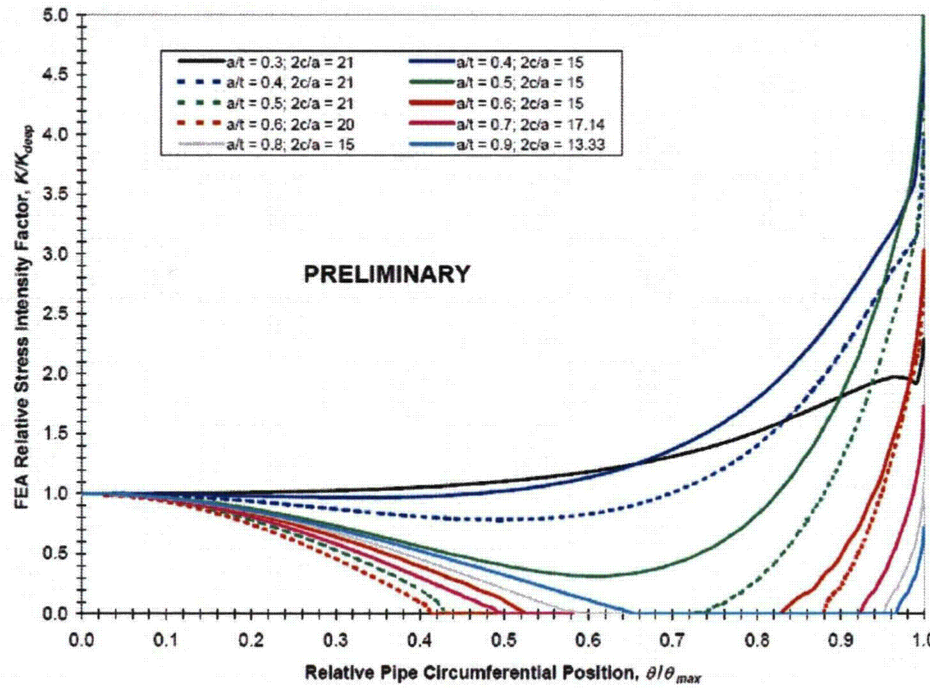




White Paper Section 5 Calculation

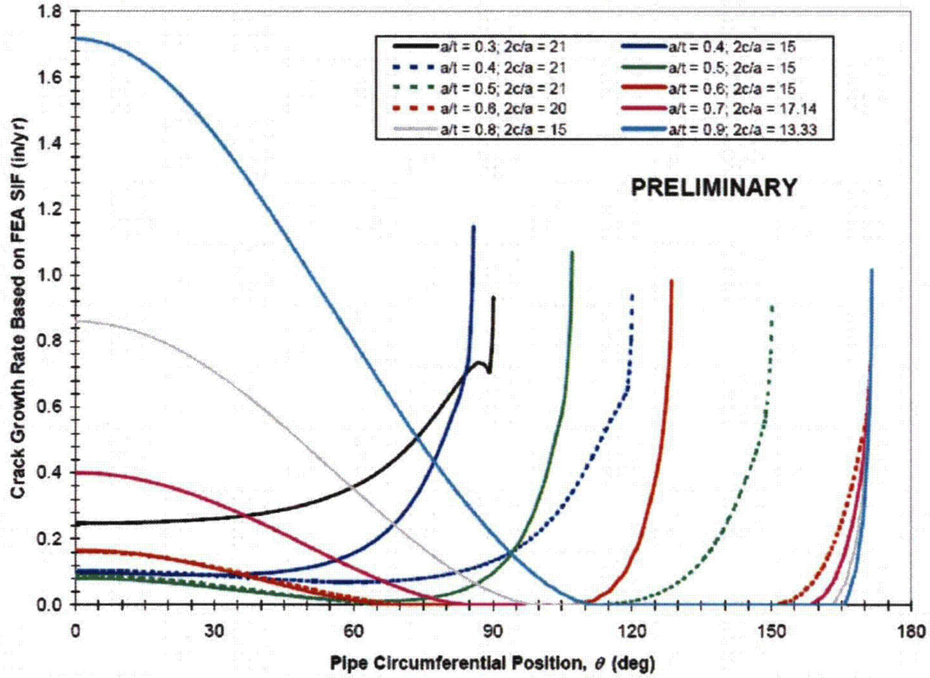
Supplemental Interpretation of Results:
SIF Along Crack Front for Matrix of Semi-elliptical Crack Cases

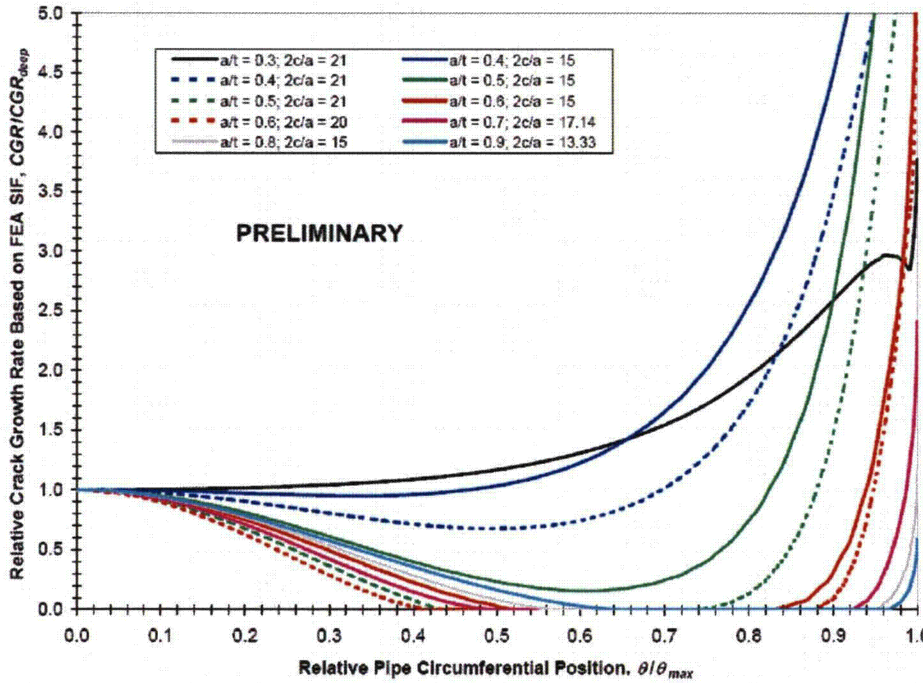




White Paper Section 5 Calculation

Supplemental Interpretation of Results:
CGR Corresponding to SIF Along Crack Front

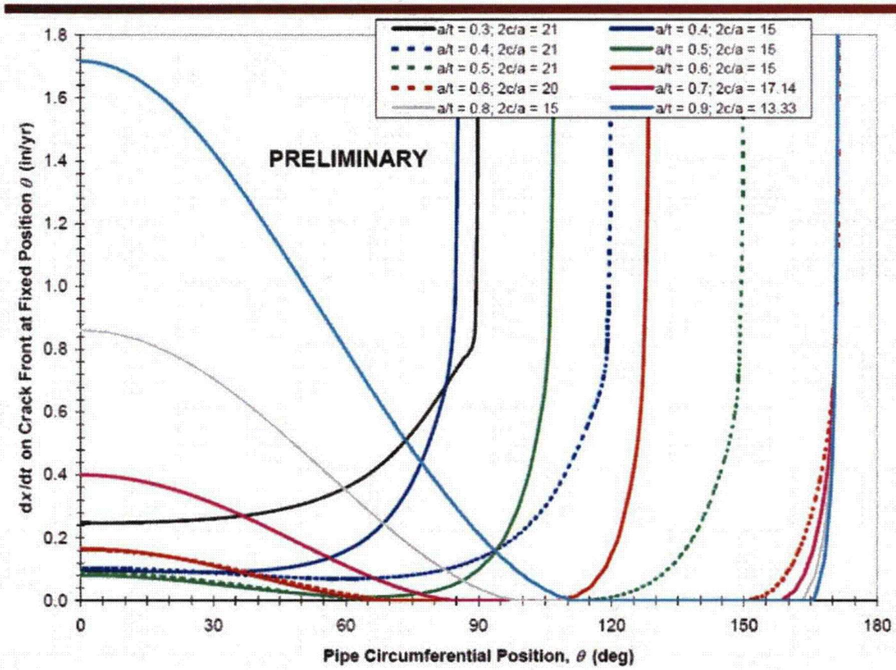


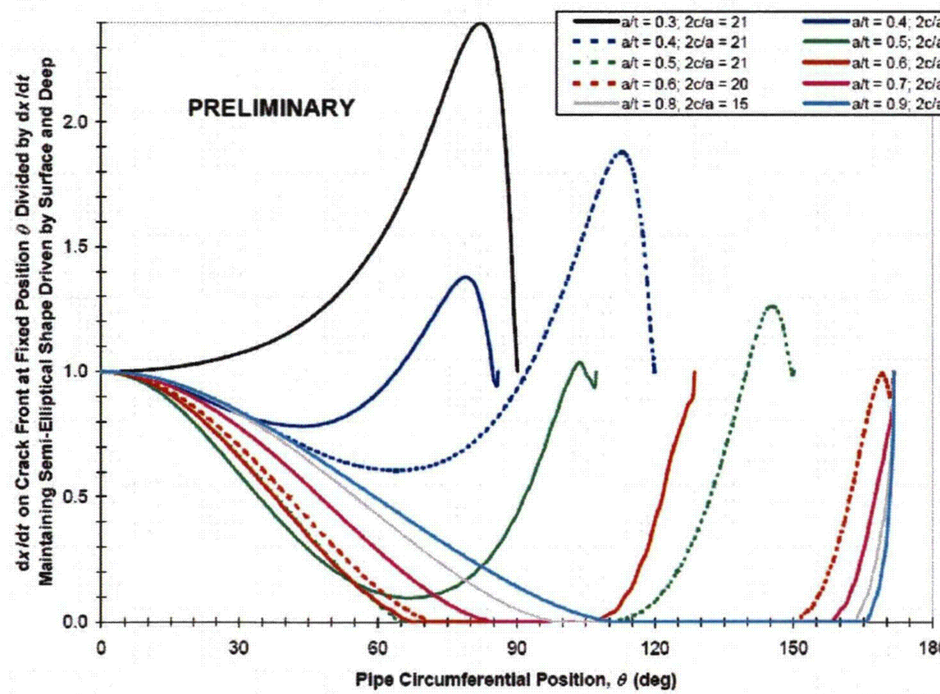


Dominion Engineering, Inc.

White Paper Section 5 Calculation

Supplemental Interpretation of Results: Radial Rate of Movement of Crack Front (dx/dt) vs Semi-elliptical Shape

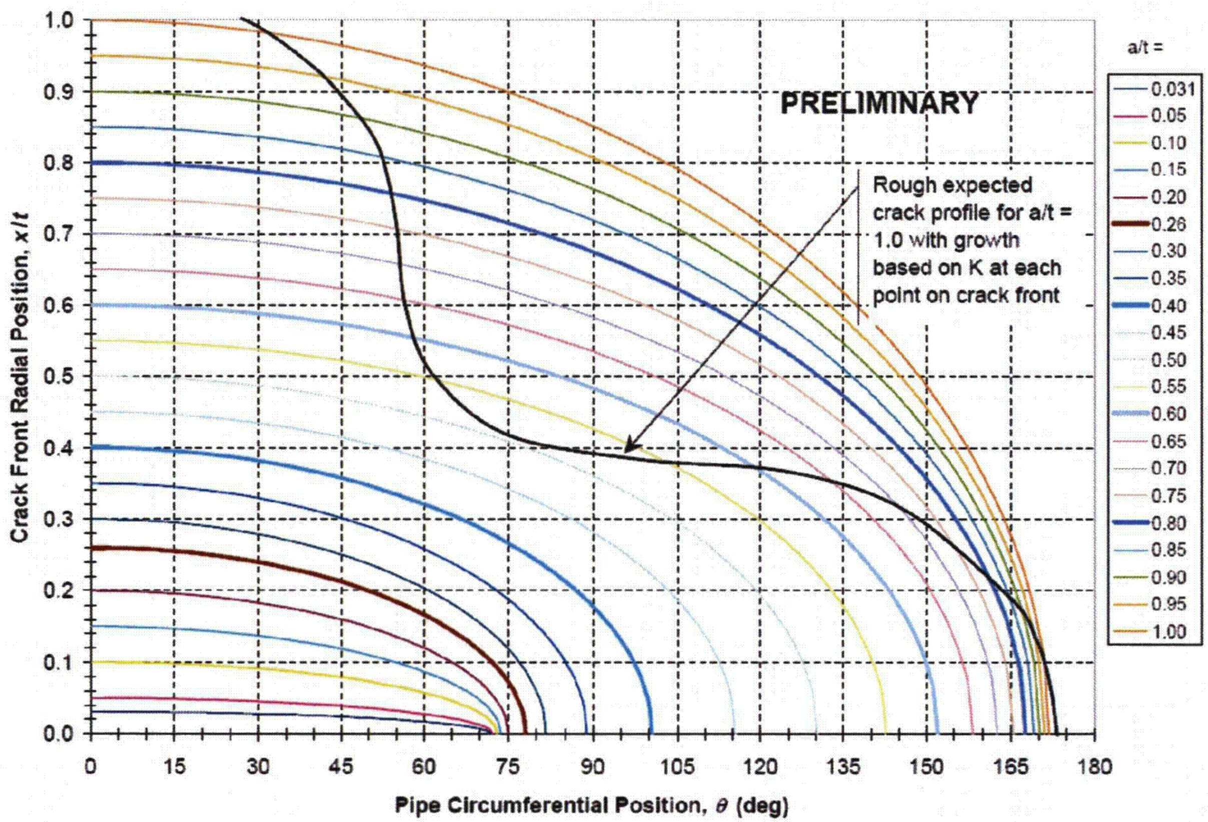




White Paper Section 5 Calculation

Supplemental Interpretation of Results:
Rough Expected Profile at Through-Wall Penetration

- Based on the SIF at each point on crack front, a significantly more stable crack profile is expected at time of through-wall penetration
- Because of effect of crack shape on SIF, evaluation of crack shape must be considered in order to confirm results



Project Plan
Summary

- Task 1: Software Development
  - Automated growth of surface crack with arbitrary shape
  - Automated growth of through-wall crack with arbitrary shape
  - Stability calculation for surface and through-wall cracks with arbitrary shape
  - Contact plane to simulate nonlinear effect of partial crack tip closure
- Task 2: Phase I Calculation
  - Repeat White Paper calculation for Wolf Creek relief nozzle indication, but with changing crack shape based on stress intensity factor calculated at each point on crack front
- Task 3: Phase II Calculations
  - Detailed sensitivity studies, benchmarking, and validation work
- Optional Task 4 Calculations
  - Sensitivity cases with crack mesh inserted directly into three-dimensional welding residual stress FEA model

Project Plan
Schedule Chart

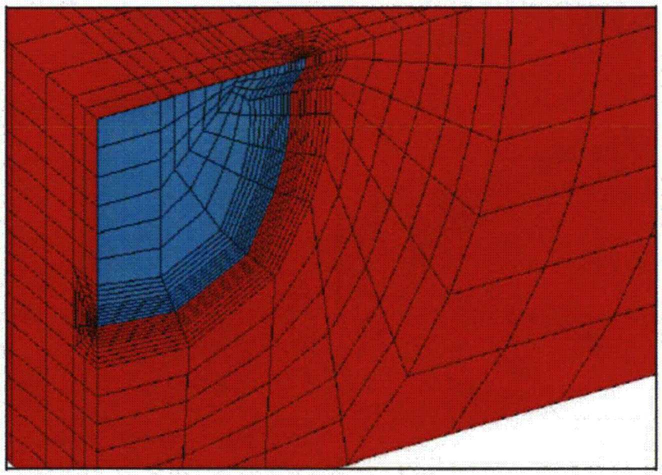
ID	Task Name	Duration	Start	Finish
1	**Software Development**	**56 days**	**Mon 1/22/07**	**Mon 4/9/07**
2	Meeting in Boulder	1 day	Mon 2/12/07	Mon 2/12/07
3	**Part-Depth**	**29 days**	**Mon 1/22/07**	**Thu 3/1/07**
8	**Thru-Wall**	**28 days**	**Thu 3/1/07**	**Mon 4/9/07**
11	**Phase I**	**13 days**	**Thu 3/1/07**	**Mon 3/19/07**
17	**Phase II**	**126 days**	**Mon 2/5/07**	**Mon 7/30/07**
18	Gather geom, load params for 9 plants	31 days	Mon 2/5/07	Mon 3/19/07
19	Verification	47 days	Mon 3/5/07	Tue 5/8/07
20	FM Position Paper	79 days	Mon 2/12/07	Thu 5/31/07
21	**Residual Stress**	**67 days**	**Mon 2/12/07**	**Tue 5/15/07**
27	**Critical Size**	**56 days**	**Mon 2/12/07**	**Mon 4/30/07**
33	**Case Matrix**	**70 days**	**Mon 3/12/07**	**Fri 6/15/07**
38	**Multiple Cracks**	**77 days**	**Thu 3/1/07**	**Fri 6/15/07**
42	**Validation**	**85 days**	**Mon 2/19/07**	**Fri 6/15/07**
48	**Consensus (Industry & NRC)**	**76 days**	**Tue 3/6/07**	**Tue 6/19/07**
49				
50	Status & Phase II review mtg (tentative)	1 day	Wed 3/7/07	Wed 3/7/07
51				
52	Conf call Phase I results (tentative)	1 day	Wed 3/14/07	Wed 3/14/07
53	Conf call #1 on Phase II progress	0 days	Tue 4/10/07	Tue 4/10/07
54	Phase II independent review meeting	1 day	Tue 5/8/07	Tue 5/8/07
55	Conf call #2 on Phase II progress	0 days	Tue 5/29/07	Tue 5/29/07
56	Present Phase II results	1 day	Tue 6/19/07	Tue 6/19/07
57	**DEI OPTIONAL SUBTASKS**	**51 days**	**Mon 3/12/07**	**Mon 5/21/07**
60	**Report**	**49 days**	**Tue 5/1/07**	**Fri 7/6/07**
65	**Deliverable - EPRI report**	**65 days**	**Tue 5/1/07**	**Mon 7/30/07**

Project Plan
Current Status

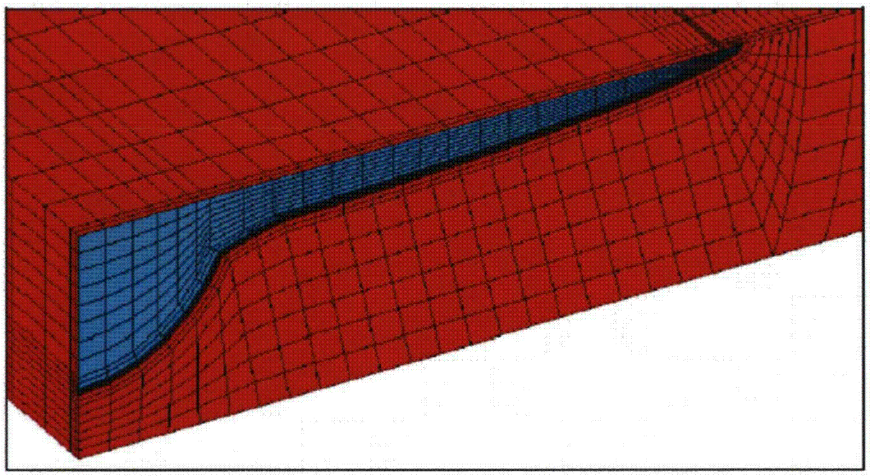
- Task 1: Software Development
  - First release of new software features on March 1 per schedule
  - Through-wall crack features are not needed for Phase I calculation, and will be completed in parallel with Task 2
- Task 2: Phase I Calculation
  - Formal DEI calculation note on schedule for March 19
- Task 3: Phase II Calculations
  - Planning for Phase II completed to support March 7 review meeting
- Optional Task 4 Calculations
  - FEACrack software extension for Task 4 would be made beginning in April

Project Plan
Task 1: Software Development

- Task 1: FEACrack Software Development
  - Automated growth of surface crack with arbitrary shape
  - Automated growth of through-wall crack with arbitrary shape
  - Stability calculation for surface and through-wall cracks with arbitrary shape
  - Increased flexibility for FEACrack to control ANSYS model
  - Contact plane to simulate nonlinear effect of partial crack tip closure



Example of custom surface crack



Example of a long surface crack with a change of profile

Project Plan
Task 1: Software Development

- Enhancements to Quest Reliability's FEACrack software are being performed to support the crack growth calculations
  - Quest Reliability's effort is being led by Dr. Ted Anderson and Dr. Greg Thorwald
  - FEACrack in combination with ANSYS was used by DEI to perform the White Paper Section 6 crack growth calculation
  - The new FEACrack features will automate the crack growth simulation for surface and through-wall cracks
    - Crack growth at each point on the crack front based on stress intensity factor calculated for that point
    - Automation of crack growth calculation permits evaluation of large matrix of sensitivity cases
  - Limit load evaluation also being automated to allow determination of end point for stress corrosion crack calculation
  - The software modifications in progress are discussed further in Dr. Anderson's separate presentation

Project Plan
Task 2: Phase I Calculation

- Repeat White Paper calculation for Wolf Creek relief nozzle indication, but with changing crack shape based on stress intensity factor calculated at each point on crack front
  - Identical relief nozzle weld OD and wall thickness as assumed in NRC calculation presented on November 30, 2006
  - Identical treatment of pipe loads for crack growth as assumed in NRC calculation presented on November 30
  - Assumption of same relief nozzle welding residual stress (WRS) profile as for November 30 NRC calculation
    - no WRS
    - 54 ksi WRS at ID
  - Use of deterministic MRP-115 crack growth equation for Alloy 182 weld material (as for November 30 NRC calculation)
  - Realistic treatment of pipe loads in critical crack size calculation
  - Evaluate effect of more realistic crack shape development on time between through-wall penetration and leakage

Project Plan
Task 2: Phase I Calculation (cont'd)

- Repeat White Paper calculation for Wolf Creek relief nozzle indication, but with changing crack shape based on stress intensity factor calculated at each point on crack front
  - Software verification activities to ensure correct numerical results for stress intensity factor given assumed geometry and loading
  - Formal DEI calculation note with Phase I result due March 19
  - Draft calculation note will be reviewed by expert panel

Project Plan
Task 3: Phase II Calculations

- Perform detailed sensitivity studies, benchmarking, and validation work specific to the pressurizer nozzle DM welds in the 9 spring 2008 plants to evaluate the viability of leak before break for these welds
  - Collection of geometry, loading, and weld repair data for 9 spring 2008 plants
  - Position paper on fracture mechanics basis for stress intensity factor calculation
  - Further software verification activities
  - Treatment of welding residual stress
  - Critical crack size calculation basis
  - Setting and evaluation of matrix of sensitivity cases using cylindrical shell geometry
  - Evaluation of effect of multiple flaws
  - Model validation efforts
  - Participation of industry and NRC experts to build consensus
  - Probabilistic calculation to investigate likelihood that the Wolf Creek indications were really growing as rapidly as assumed in the White Paper and NRC calculations
  - Final report with methodology, results, and validation in EPRI format

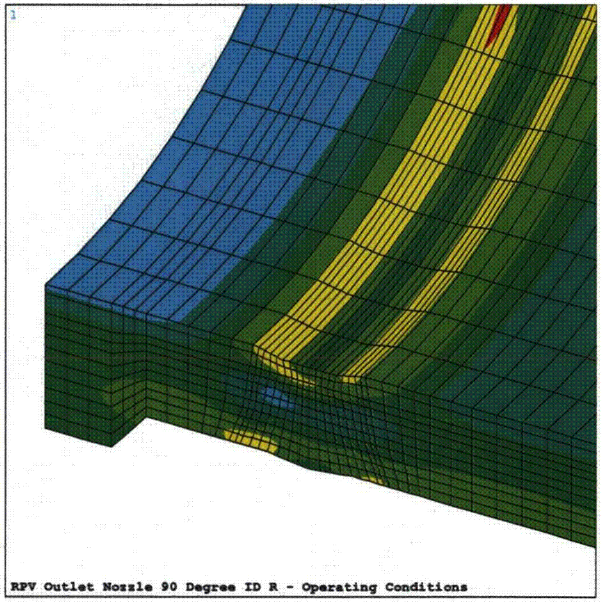
Project Plan
Optional Task 4 Calculations

- Perform selected sensitivity cases with crack mesh inserted directly into three-dimensional welding residual stress FEA model:
  - More precise calculation of stresses for nozzle-to-safe-end geometry
  - Direct input of welding residual stresses from welding residual stress FEA model, rather than user selection of welding residual stress cases
  - Consideration of secondary effects such as local thermal stresses due to difference in coefficient of thermal expansion for each material
  - Because this modeling is more labor- and CPU-intensive compared to modeling using cylindrical shell geometry and residual stresses simulated via temperature field input, this model will be used to evaluate a subset of the full matrix of cases
  - The cylindrical shell model also has the advantage of allowing direct comparison with published stress intensity factor solutions, including those considering the standard ASME welding residual stress assumptions

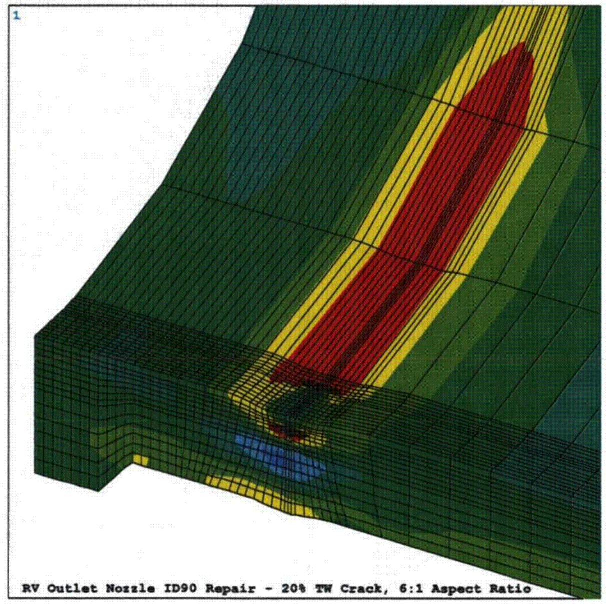
Project Plan

Optional Task 4 Calculations

- This type of approach was applied in a preliminary fashion by DEI in 2005 for a reactor pressure vessel outlet nozzle



Intact Axial Operating Stresses

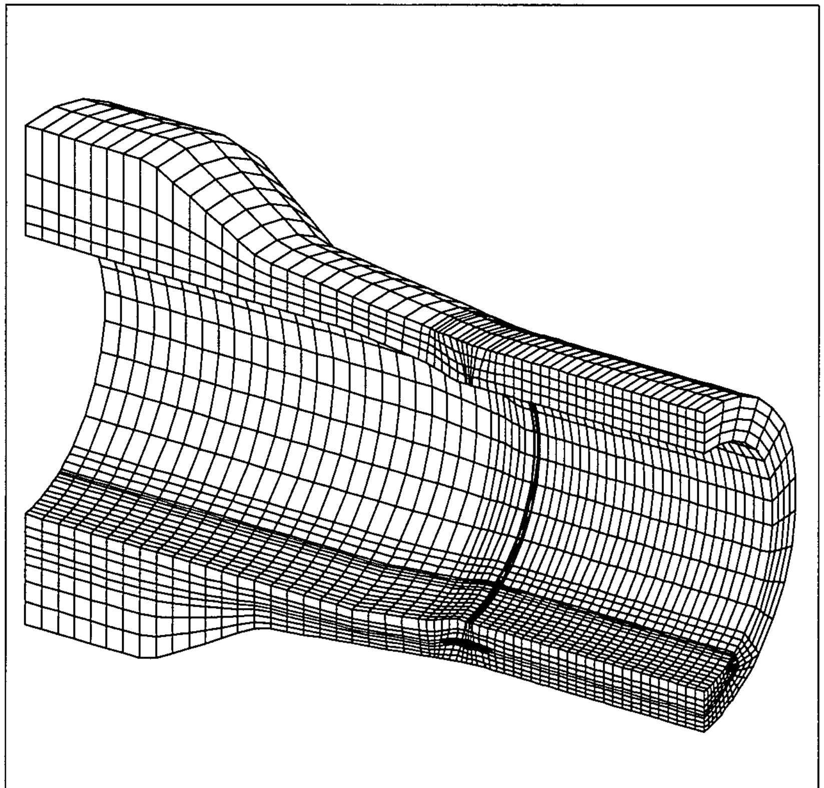


Axial Stress Redistribution with Circ Crack

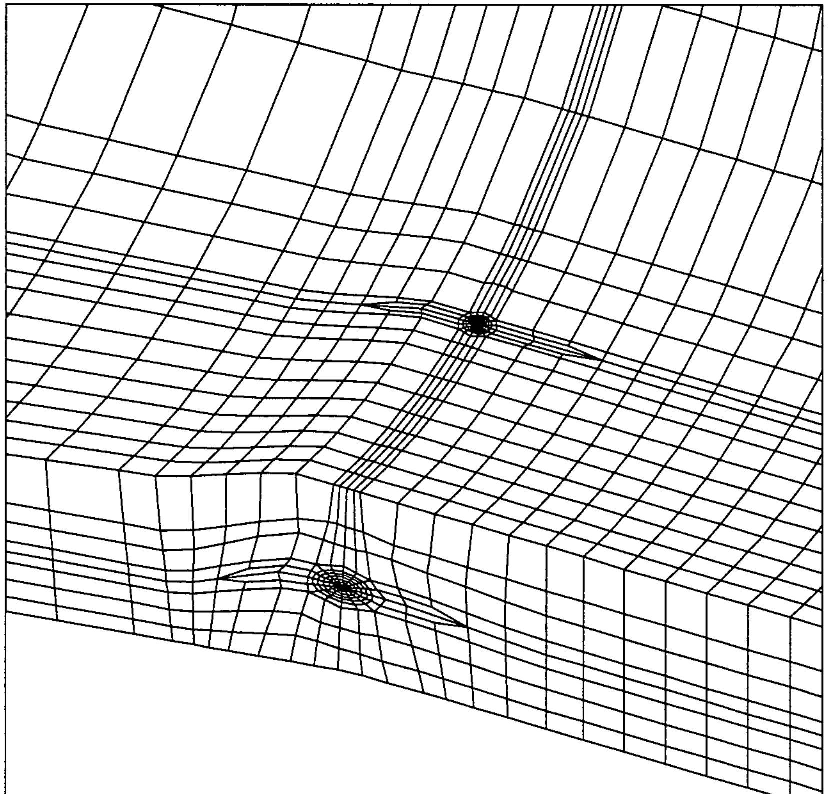
- The FEACrack enhancement for Task 4 will reduce the effort required to insert the crack mesh submodel into the full welding residual stress model

Project Plan
Optional Task 4 Calculations

- Another previous example of insertion of crack into WRS model (pressurizer surge nozzle)



Surge Nozzle ID30 Repair - 60% TW Crack, 6:1 Aspect Ratio



Surge Nozzle ID30 Repair - 60% TW Crack, 6:1 Aspect Ratio

Eight Initial NRC Comments

1. Benchmarking
2. Validation
3. Safety Factor
4. Weld Residual Stresses
5. Multiple flaws and flaw size
6. Crack growth rates
7. Predicting growth by K
8. Non-idealized surface and through-wall crack stability

Discussion of Proposed Technical Approach

- The balance of this presentation addresses the various technical items that should be considered as part of the evaluations being performed
- To facilitate discussions of the expert panel, for each item, DEI has listed its planned approach
- The objective of the expert discussions on March 7 is to reach consensus on the appropriate approach for as many items as possible
- For some items, some additional work will be required before a exact technical position can be finalized; the expert discussions will help to define the process needed to reach consensus on such items

Discussion of Proposed Technical Approach (cont'd)

- Specific items for reaching consensus are identified in following slides using this symbol:

- The minutes of the March 7 meeting will reflect the results of the discussions of the expert panel for each of these items.

Discussion of Proposed Technical Approach
Outline of Technical Items

- Approach to:
  1. defining model geometry
  2. defining pipe loads for crack growth
  3. defining welding residual stress inputs
  4. application of crack growth rate equation
  5. treatment of developing crack shape
  6. defining pipe loads for critical crack size
  7. calculating critical crack size
  8. consideration of multiple cracks
  9. design of sensitivity case matrix
  10. verification of stress intensity factor calculation
  11. validation of welding residual stress inputs
  12. validation of overall crack growth model
  13. additional meetings of the expert panel and project communication
  14. others such as leak rate modeling

1. Defining Model Geometry

- Basic weld design dimensional data (OD and wall thickness) are now being gathered for all 53 pressurizer nozzle DM welds in the group of 9 spring 2008 plants
  - Many of the 53 welds are expected to have identical dimensions
  - All 6 Wolf Creek welds are also included
- The Phase II calculations will cover the full range of OD and wall thickness using the simplified cylindrical shell geometry previously applied for the White Paper calculations
  - Available as-built weld dimensional data will be applied in a set of sensitivity cases
- The optional scope provides for additional analysis cases with the crack mesh inserted directly into the DEI WRS FEA model, allowing consideration of the detailed nozzle-to-safe-end geometry
- The nonlinear effect of partial crack closure on the SIF will be examined for selected sensitivity cases
- Is there consensus on this approach to considering the weld geometry?

2. Defining Pipe Loads for Crack Growth

- Design pipe loads are now being collected for each of the 53 subject welds
- Changes in pipe axial force and moment loads have multiple effects on the relative crack growth rate in the radial and circumferential directions
- Therefore, multiple loading cases will be considered based on the pipe loads reported for the 53 subject welds
- Is there a consensus on considering a matrix of load cases covering the design loads for the 53 subject welds?

2. Defining Pipe Loads for Crack Growth (cont'd)

- It is planned that each category of loading be treated as follows in the crack growth calculation:
  - Deadweight: Axial force and bending moment applied to end of model
  - Internal pressure: End cap axial force based on ID at weld, plus full crack face pressure applied directly to crack face for surface and through-wall cracks
  - Pipe thermal expansion: Axial force and bending moment applied to end of model (no credit conservatively taken for relaxation of load with crack opening)
  - Welding residual stress: See next section
  - Thermal stratification pipe bending moment (surge nozzle only): Considered in selected sensitivity cases
  - Cold spring loads: Considered in selected sensitivity cases
  - Local thermal stress due to differential thermal expansion (Q-stress): Considered as a sensitivity case in optional cracked WRS model
  - Seismic loads: Not relevant for crack growth
- Is there consensus on treatment of each type of loading in the crack growth calculation?
  - Welding residual stress is covered separately in next section

2. Defining Pipe Loads for Crack Growth (cont'd)

- For global moment loads, it is planned to use the following equation to calculate an effective global bending moment:

$$M_{eff} = \sqrt{M_y^2 + M_z^2 + \left(\frac{\sqrt{3}}{2}T\right)^2}$$

- The equation considers the effect of the applied torsion on the Von Mises effective stress
- This is a simplification as torsion would act as a Mode II and/or III loading on the crack
- Is there consensus on application of an effective bending moment in this manner?

3. Defining Welding Residual Stress Inputs

- Because of the uncertainty in the true residual stress field in each of the 53 subject welds, a matrix of sensitivity cases will be considered covering a wide range of WRS patterns
- The following sources will be applied to develop the WRS cases considered:
  - Weld fabrication and repair data from construction for the 53 subject welds (see next slide)
  - Previous WRS calculations by DEI and others for PWR piping butt welds
  - Limited number of DEI WRS FEA model runs for the specific geometry of some of the 53 subject welds considering the weld fabrication information (see next slide)
  - WRS data in the open literature including BWR mockup data used to develop the ASME standard WRS distributions

3. Defining Welding Residual Stress Inputs

Weld Fabrication and Repair Data Compiled for Wolf Creek

- Data on initial weld fabrication and repair has also been compiled for the subject welds in the 9 spring 2008 plants
- These data will be evaluated and then used to help guide selection of WRS inputs to the crack growth model
- The DEI WRS model will be used to investigate some weld repair cases for nozzle-to-safe-end geometries specific to the 9 plants

Defect Location and Description	Repair Description
Surge Nozzle Welds	
1. Not enough weld build-up on buttering	A182 added
2. During Repair #1 RT found (2) OD indications	Indications removed, repaired with A182, PT
3. Safe end RT showed (1) ID flaw 0.20/0.44	Indication removed, repaired with A82, PT/RT
4. Cuts made in surge nozzle SS clad to check thickness	Cuts repaired with 308L and inspected
5. With completed PZR on rail car it was discovered that Repair #4 had not been PT inspected after PWHT	Unpacked PZR, thermal sleeve removed by grinding, Repair #4 weld removed/inspected/rewelded with 308L & 309L, local PWHT, PT of repair, and thermal sleeve reinstalled by A82 weld
Spray Nozzle Welds	
6. PT indications found on build-up prior to PWHT	Indications removed, repaired with A82, PT
Safety Nozzle "A"	
7. Butter grind cuts to 1/8" needed to clear PT	Repaired with A182, PWHT, PT
8. Safe end RT showed (2) ID flaws 0.34/1.25, 0.34/0.875	Indications removed, repaired with A82, PT/RT
Safety Nozzle "B"	
9. Safe end RT showed (6) ID flaws 0.5/1.0 to 0.75/2.5	Indications removed, repaired with A82, PT/RT
10. Repair #9 did not include proper cleaning step	Repairs #9 removed, repaired with A82, PT/RT
11. SS safe end ID too large	Added 308L to ID, machined, PT
Relief Nozzle	
12. Butter grind cuts needed to clear PT	Repaired with A82/182, PWHT, PT
13. Butter and clad RT showed (1) ID flaw 0.44/0.5 and (1) OD flaw 0.44/1.0	Indications removed, repaired with A82, PWHT, PT/RT
14. Additional butter OD flaw (1) 0.75/1.0	Indication removed, failed RT, additional material removed, repaired with A182, PT/RT, PWHT
15. Additional butter ID flaws (3) 0.75/0.75 to 0.75/2.25	Indications removed, repaired with A82
16. Additional butter OD flaws after PWHT 0.75/0.5 to 0.75/2.25	Indications removed, repaired with A82, PT
17. ID of butter and cladding damaged during Repair #16. PT of damaged area showed ID indications	Clad weld repaired with A82, ground to clean up surface, PT
18. Safe end RT showed (1) OD flaw 0.5/1.25	Indication removed, weld repaired with A82,PT/RT
19. Safe end RT showed (1) ID flaw 0.5/0.5	Indication removed, weld repaired with A82, PT/RT
20. Safe end ID exceeded drawing maximum	Applied 308L buildup, machined, PT
21. PT after PWHT and hydro showed ID indications 1.88" long, 2.38" wide and 0.50" deep	Indication removed, weld repaired with A82.PT

Notes:
(1) Sequence numbers agree with Reference Repair Numbers in Westinghouse evaluation.
(2) See complete Westinghouse evaluation for further details.
(3) Code for flaws is Depth / Length.

Source: *MRP 2007-003 Attachment 1 (White Paper).*

3. Defining Welding Residual Stress Inputs (cont'd)

- Patterns of WRS variability will be considered in both the radial and circumferential directions
- For the cylindrical shell SIF model, the WRS will be simulated using an applied thermal input pattern, which may vary in the radial and circumferential directions
  - Simulation of WRS using thermal strains is a standard technique
  - The axial extent of the applied temperature load will be conservatively chosen based on the design length of the DM weld
  - This length will be varied in sensitivity cases to check for the effect of residual stress relaxation
- For selected sensitivity cases of the optional SIF modeling, the 3-dimensional WRS field from the DEI intact WRS FEA model will be directly input to the cracked SIF model
- Is there consensus on this basic approach to treatment of WRS in the crack growth calculations?

4. Application of Crack Growth Rate Equation

- For most cases, the MRP-115 deterministic crack growth rate (CGR) equation will be applied to calculate the CGR as a function of the SIF
  - No credit for a SIF threshold
- Sensitivity cases may examine effects such as:
  - Uncertainty in the SIF power-law exponent (nominal 1.6)
  - Uncertainty in power-law constant (only time scaling factor that would affect time between leakage and rupture but not viability of LBB)
  - Lower CGR for Alloy 82 root passes versus Alloy 182 passes (factor of 2.6)
  - Lower CGR for growth perpendicular to dendrite solidification direction (factor of 2.0)
- Fatigue crack growth will not be explicitly calculated based on general result that PWSCC is the significant concern
- Potential for stable mechanical growth governed by EPFM will be considered as part of EPFM critical flaw size sensitivity
- Is there consensus on calculation of the CGR?

5. Treatment of Developing Crack Shape

- The crack growth model will consider the change in crack shape that results from the variation in SIF along the crack front as previously described
  - Assumption of semi-elliptical shape becomes unrealistic for large cracks calculated to have partial crack tip closure based on assumed loads
- The possibility of variation in the CGR governing equation at different points along the crack front (power-law constant and exponent) may be considered as sensitivity cases in combination with other complexities such as the lower CGR expected for the Alloy 82 root pass material at the ID surface
- Is there consensus on the treatment of crack shape evolution?

6. Defining Pipe Loads for Critical Crack Size

- It is planned that each category of loading be treated as follows in the critical crack size calculation that defines the growth end point:
  - Deadweight: Same as for growth
  - Internal pressure: Same as for growth
  - Pipe thermal expansion: Not included because this displacement-controlled load generates stresses that are, by design, in the elastic range only. A small amount of plastic strain will therefore relieve this load entirely, and the load will not contribute to rupture
  - Welding residual stress: Not included in limit load mechanism, but possibly considered as an input to EPFM sensitivity cases
  - Thermal stratification pipe bending moment (surge nozzle only): Not included for same reason as for pipe thermal expansion
  - Cold spring loads: Not included for same reason as for pipe thermal expansion
  - Local thermal stress due to differential thermal expansion (Q-stress): Not included as this is another secondary stress component
  - Seismic loads: SSE load considered for faulted cases
- Is there consensus on treatment of each type of loading in the critical crack size calculation?

7. Calculating Critical Crack Size

- It is planned that the stability of the crack at each step in the crack growth process will be checked using the limit load method by comparing the elastic Von Mises effective stress averaged over the remaining weld cross section versus the Alloy 182 flow strength at temperature
  - Surface and through-wall cracks
  - This is an improvement over standard models that assume standard crack shapes
- The Alloy 182 flow strength is appropriately based on data published by INCO for as-deposited Alloy 182 weld metal
  - Supported by Wolf Creek CMTRs for Alloy 182
- The potential concern for an EPFM failure mode occurring before the limit load failure will be considered in selected sensitivity cases
- Is there consensus that this approach is appropriate for calculating the crack growth end point?

8. Consideration of Multiple Cracks

- As demonstrated by practical experience such as apparently for the Wolf Creek pressurizer surge nozzle, there is the possibility of multiple growing flaws connected to the weld ID
- The project will explicitly consider this concern; several potential approaches are under active consideration:
  - Enveloping of multiple initial flaws with one modeled flaw
  - Modeling of a part-depth 360° flaw with a variable depth around the circumference
  - Static FEA SIF modeling of two separated flaws to investigate influence of each flaw on the other as a function of their separation on the weld ID
- Open discussion on consideration of effect of multiple flaws

  - Scoping evaluations will be completed to help define approach to multiple flaws

9. Design of Sensitivity Case Matrix

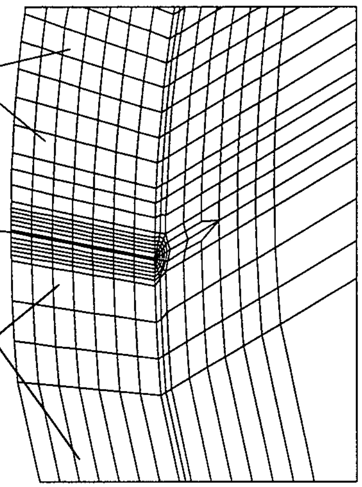
- In Phase II, a matrix of cases will be considered in order to bound the crack growth results for the set of 53 pressurizer nozzle DM welds in the 9 spring 2008 plants and to address modeling uncertainties
  - weld diameter and thickness
  - crack initial size and shape
  - pipe loads
  - simulated welding residual stress
  - weld flow strength
- The optional scope provides for additional cases with the crack mesh inserted directly into the DEI WRS FEA model
- Is there consensus on including these parameters in the sensitivity case matrix?

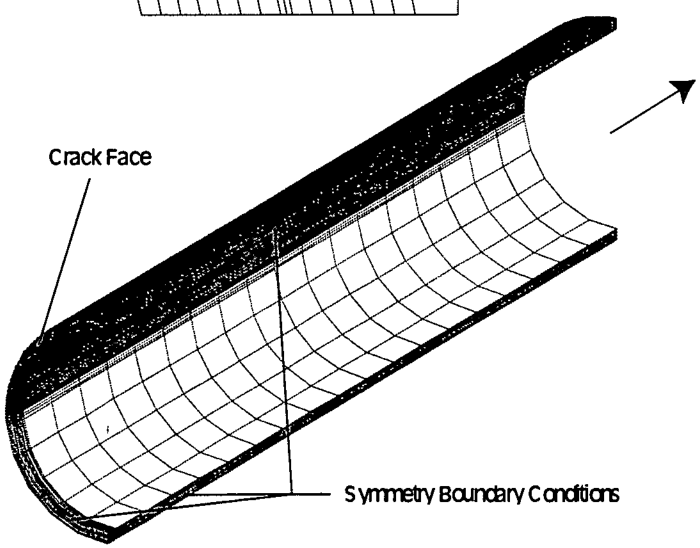
10. Verification of SIF Calculation

- Both the Phase I and II work include tasks to verify that the FEACrack/ANSYS software including new modules is producing mathematically correct answers
- Surface and through-wall crack test cases will be compared against published solutions
  - Newman-Raju published solutions
  - EPRI Ductile Fracture Handbook (Zahoor) solutions
  - WRC Bulletin 471 (Anderson et al.)
  - Selected cases performed by NRC contractor (EMC2)
- DEI is also performing general commercial software dedication of the FEACrack software per EPRI guidance
- In addition, a position paper will be produced on the fracture mechanics basis behind the FEACrack software applied
- Is there consensus on this approach to verification of the FEACrack software being applied?

10. Verification of SIF Calculation

Past Example 1: TW Circ Flaw in Cylinder



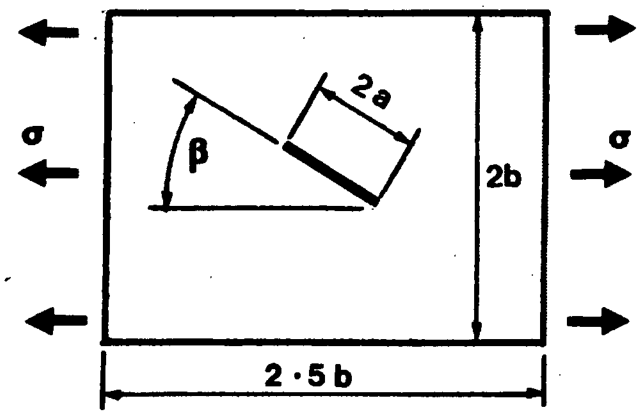


- Axially loaded through-wall flaw circumferential in cylinder
- SIF for model compared with EPRI Ductile Fracture Handbook results
  - R/t = 10, max arc = 180°
- Results agree within 10%

Crack Length	K_I Calculated Using Zahoor[1]	K Calculated per FEA Model Test Case
30°	2.9 ksi√in	2.9 ksi√in
80°	6.6 ksi√in	7.1 ksi√in
130°	12.7 ksi√in	13.6 ksi√in
180°	24.0 ksi√in	26.5 ksi√in

10. Verification of SIF Calculation

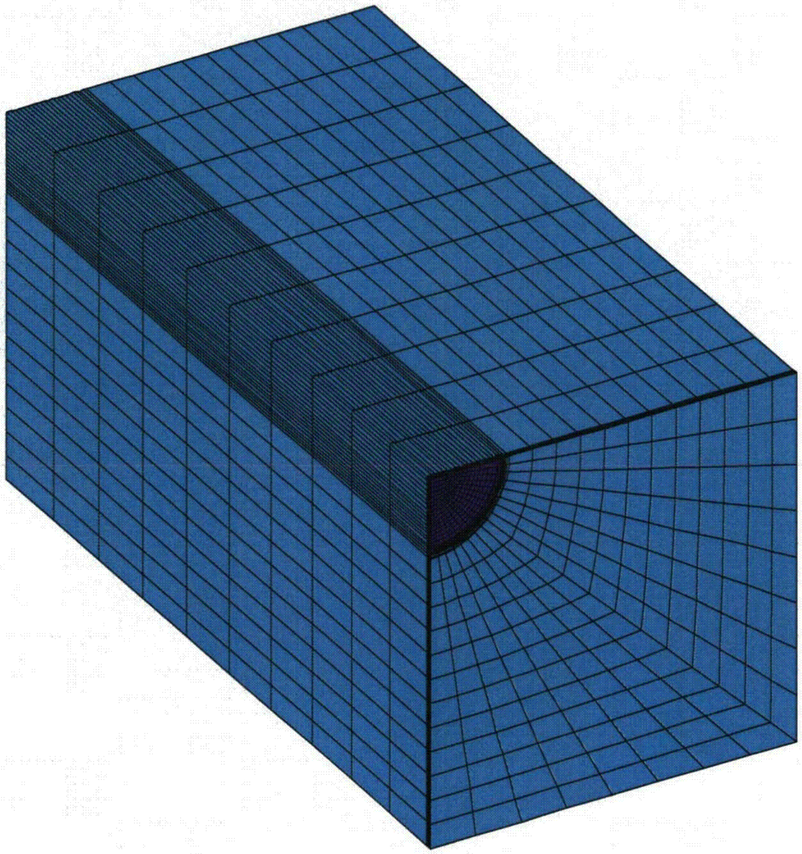
Past Example 2: Angled Crack in a Plate



- Model test performed to examine J-integral results with combined crack opening modes (I and II)
  - Flaw 45° from horizontal
- Model dimensions selected such that $K_I = K_{II} = 6.3$ ksi$\sqrt{\text{in}}$
- Combined J-integral = 2.62 in-lbs/in^2
- FEA results for average J-integral on crack front = 2.66 in-lbs/in^2

10. Verification of SIF Calculation

Past Example 3: Corner Crack on Plate Face



- Applied crack face pressure of 50 ksi
- Rooke and Cartwright peak SIF = 72.2 ksi$\sqrt{\text{in}}$
- FEA results = 69.6 ksi$\sqrt{\text{in}}$

11. Validation of WRS Inputs

- A two-step process to model validation is envisioned:
  - Validation of residual stress assumptions based on available stress measurements, model predictions, and the general WRS literature
  - Validation of the overall crack growth model based on available destructive examinations results for weld metal applications and other information
- Various sources of WRS information will be sorted and organized to support range of WRS cases considered in the calculations:
  - Mockup stress measurements
  - Stress measurements on removed plant components
  - Various FEA models including DEI, SI, EMC2, etc.
  - General WRS literature

11. Validation of WRS Inputs (cont'd)

- The results of the DEI WRS model have shown reasonable agreement versus measured WRS:
  - Measured CRDM nozzle mockup stress
  - Measured BWR shroud support weld stress
  - Measured CRDM nozzle ovality
- Discussion of sources of data for validation of WRS assumptions

Welding Residual Stress Model Validation

General Model Background

- Independent welding residual stress models have been developed by many industry and regulatory consultants
- DEI model originally developed in 1990 to simulate J-groove attachment welds of pressurizer heater sleeves
  - Expanded to include other nozzle penetrations with J-groove welds since 1991
  - Expanded to butt welds in 1995 (stainless steel) and 1997 (Ni base alloys)
  - Expanded to various nozzle repair methodologies since 2002
- Consistent analysis methodology has been used since initial development of welding residual stress model
  - Thermal model simulates weld heating and cooling using idealized target temperatures for weld center and HAZ
  - Structural model uses temperatures from thermal model to simulate thermal expansion followed by weld strengthening with cooling

Welding Residual Stress Model Validation

Model Background

- Welding residual stress calculations have been performed for a variety of Ni base alloy welds
- J-groove welds for a wide range of nozzle penetration types (e.g., CRDM, heater sleeve, etc.)
- Piping butt welds for sizes ranging from RPV outlet to 1-inch diameter nozzles
- All major nozzle repair types
  - Nozzle left in place (ID inlay, J-groove weld overlay)
  - Nozzle partially removed (internally or externally)
    - ID temper-bead half nozzle weld repair
    - Outer surface weld pad buildup with new J-groove weld attachment

Welding Residual Stress Model Validation

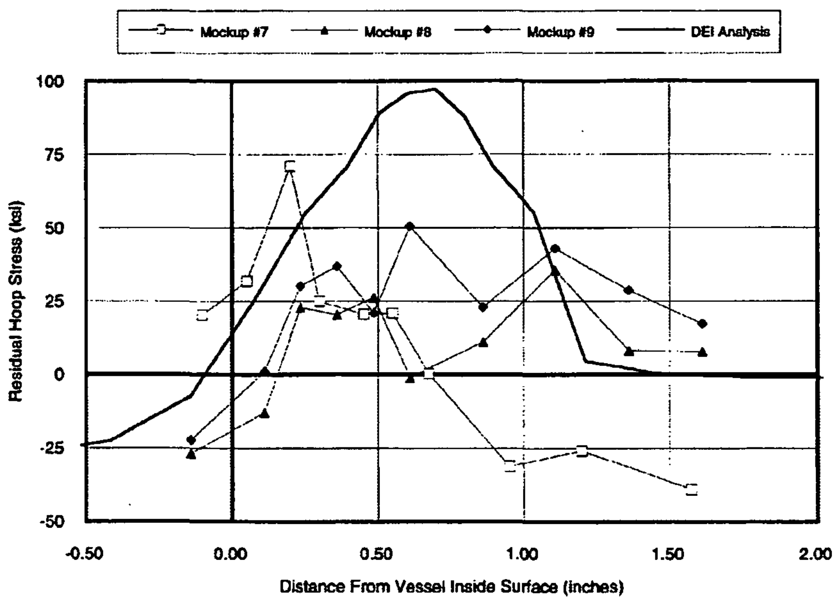
Key Reports

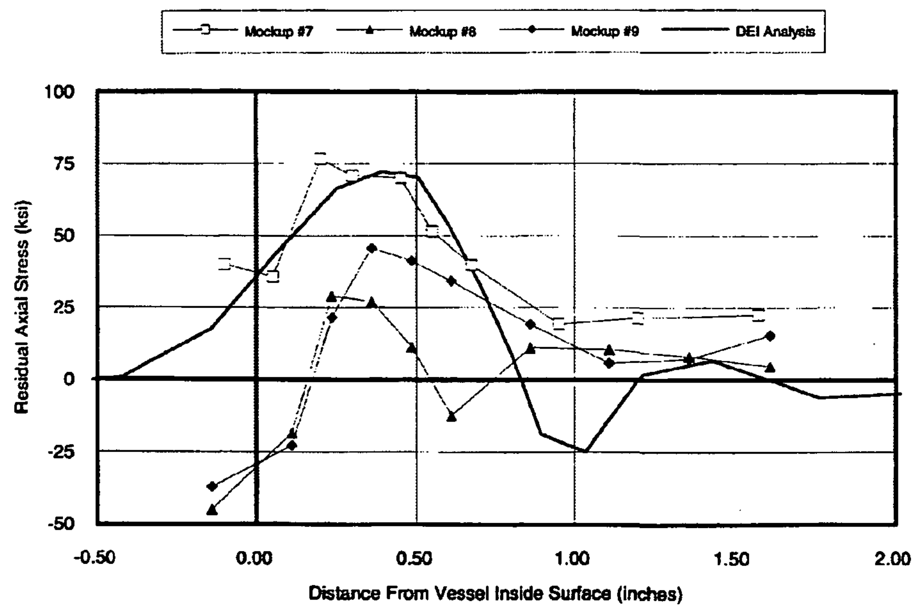
- *PWSCC of Alloy 600 Materials in PWR Primary System Penetrations*, EPRI TR-103696, July 1994.
  - Describes development of welding residual stress model properties
  - Compares model results to measured residual stresses from mockups
- *Evaluation of Crack Growth in BWR Nickel Base Austenitic Alloys in RPV Internals (BWRVIP-59),* EPRI TR-108710.
  - Shroud support welds examined (butt weld type geometries)
  - Model results compared to measured residual stresses from actual welds
- *Proceedings: 1992 EPRI Workshop on PWSCC of Alloy 600 in PWRs*. December 1993. EPRI TR-103345.
  - Overview of industry at a time when many models were being developed

Welding Residual Stress Model Validation

EPRI TR-103696

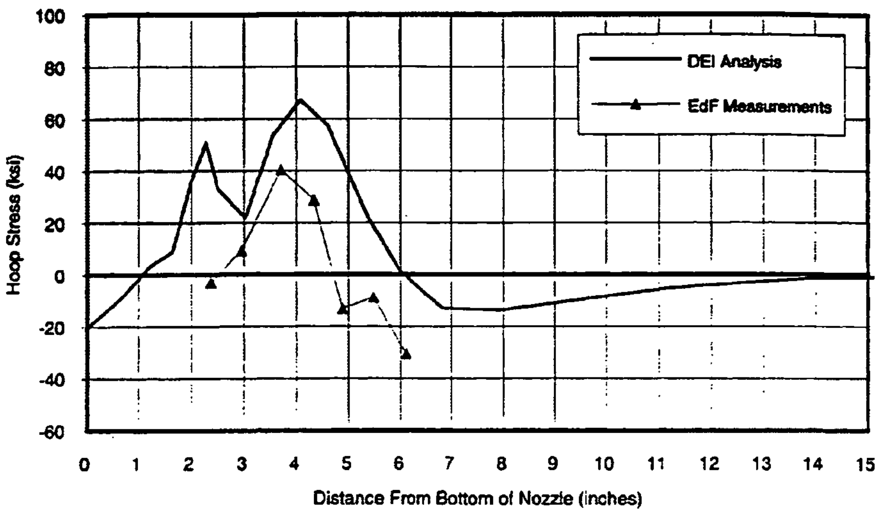
- Comparison with Combustion Engineering XRD residual stress measurements for pressurizer heater sleeve mockups at inside surface

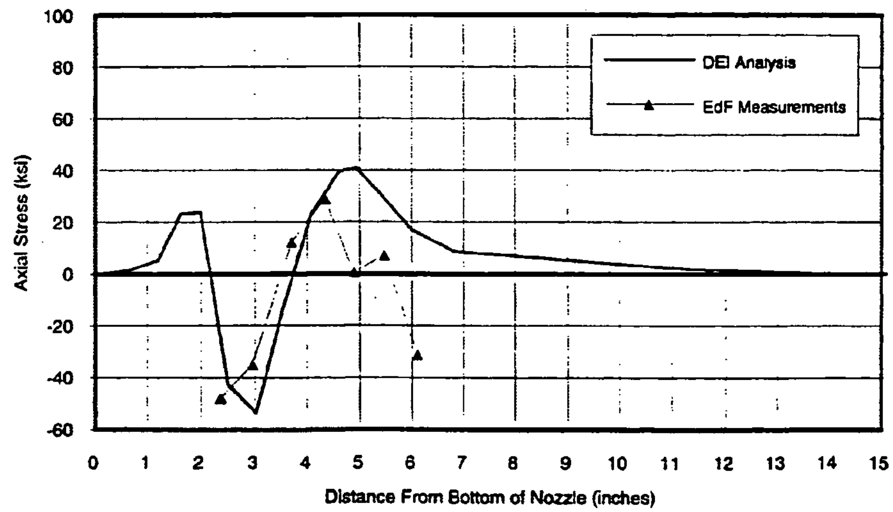




Welding Residual Stress Model Validation
EPRI TR-103696

- Comparison with EdF hole-drilling strain gauge residual stress measurements for CRDM nozzle mockups at inside surface (39° nozzle, downhill side shown)





Welding Residual Stress Model Validation

Measured Ovality

- TR-103696 reported two sets of ovality measurements taken from mockups compared to DEI analyses
  - 47° EdF CRDM: 0.064 inch measured vs 0.052 inch calculated
  - Ringhals outer row CRDM: 0.045 inch measured vs 0.049 inch calculated
- BMN analyses for South Texas compared against measured ovality for EdF plants
  - Measured ovality (average outer penetrations): 0.020 inch vs 0.0122 inch calculated

12. Validation of Overall Crack Growth Model

- The plan for Phase II includes a task to develop an approach to overall model validation based on available data sources
- Possible sources of data for validation include PWR and BWR plant experience, laboratory data, and published data for other industries
- Additional software runs are envisioned for comparison to specific validation cases
- Open discussion on validation and sources of data

13. Expert Panel Meetings / Communication

- Additional meeting and telecons are planned for purpose of:
  - Technical input and review
  - Consensus building
  - Communication with NRC and public
- Tentatively planned meetings and telecons:
  - March 14 telecon: Preliminary Phase I results
  - April 10 telecon: Telcon #1 on Phase II progress
  - May 8 meeting: Phase II review meeting
  - May 29 telecon: Telcon #2 on Phase II progress
  - June 19 meeting: Present Phase II results
- Is there consensus on this tentative meeting schedule?

14. Other Technical Approach Items

- Any others issues for discussion not yet covered?
  - leak rate modeling
  - others?