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

Sponsored by: EPRI Materials Reliability Program

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Presented To:

Expert Review Panel for Advanced FEA Crack Growth Calculations

Presented By:

Glenn White
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Dominion Engineering, Inc.

Tuesday, May 8, 2007
Status Meeting on Implications of Wolf Creek Dissimilar Metal Weld Inspections
Bethesda North Marriott Hotel and Conference Center
North Bethesda, Maryland

Topics

- Introductions – Industry and NRC
- Status of Industry work, including response to April 4, 2007 NRC letter – Industry
- Status of NRC Confirmatory Research – NRC
- Presentation & Discussion of Proposed Matrix – Industry
- Additional topics – Industry and NRC
  - Critical Crack Size Calculations (if not covered in bullet 2) – Industry
  - Validation studies and WRS mockups – Industry
  - Benchmarking NRC/Industry K Solutions for the Advanced FEA Calculations – Industry and NRC
  - Leak-rate Calculations - Industry
- Plans for next meeting(s) – Industry and NRC
- Meeting Summary and Conclusions – Industry and 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
  - Greg Thorwald, Quest Reliability, LLC
- Expert Review Panel
  - Ted Anderson, Quest Reliability, LLC
  - Warren Bamford, Westinghouse
  - Doug Killian, AREVA
  - Pete Riccardella, Structural Integrity Associates
  - Ken Yoon, AREVA
- NRC Participants
  - Al Csontos, NRC Research
  - Bob Hardies, NRC Research
  - Dave Rudland, EMC2
  - Simon Sheng, NRC NRR
  - Ted Sullivan, NRC NRR

Project Plan
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
  - Background 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

Additional Calculations with Crack Inserted into WRS Model

- 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

Work Status
Summary

- Assessment of plant-specific inputs for 51 welds in 9 spring 2008 plants
  - Dimensions
  - Piping loads
  - Available weld repair information
- Critical crack size calculations
  - Limit load calculations for through-wall flaws in 51 welds
  - Limit load calculations for part-depth flaws in 51 welds
  - Limit load calculations for custom crack profile (part-depth and through-wall)
  - Assessment of EPFM failure mode
- Crack growth calculations for custom crack shape
  - FEACrack software extensions
  - Modeling refinements
  - Effect of moment magnitude and initial crack assumption
  - Stability of calculated crack progression
  - Element and time step size refinement studies
  - Use of WRC Bulletin 471 axisymmetric solution as scoping tool

Work Status
Summary (cont'd)

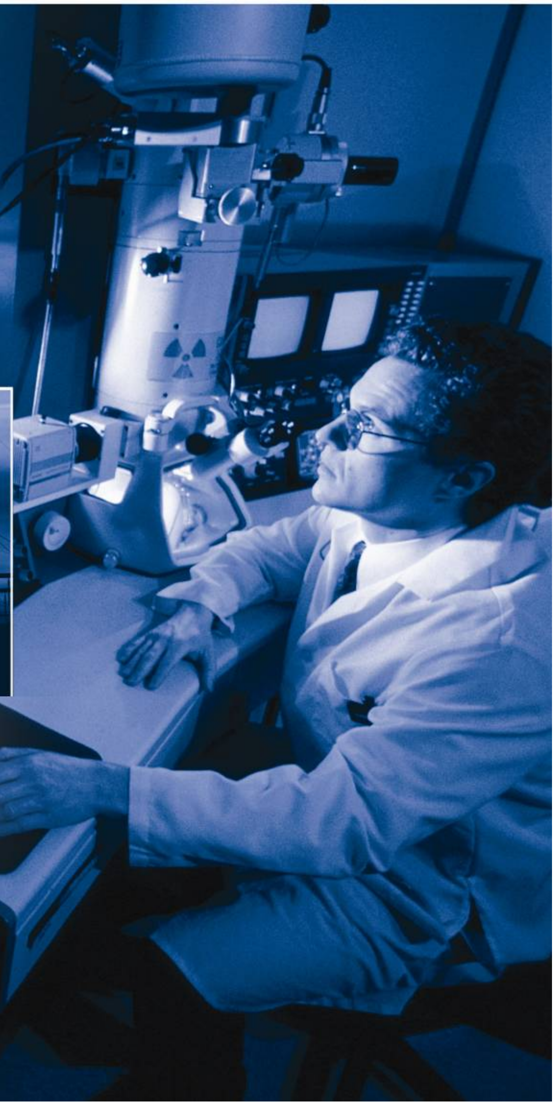
- Leak rate calculations
  - PICEP and SQUIRT models
  - Calculation of COD and leak rate using PICEP as scoping tool
  - Calculation of leak rate with COD from complex crack growth FEA calculations
- Development of matrix of WRS profiles
  - Axisymmetric (self balance at every circumferential position)
  - Non-axisymmetric (self balance over entire cross section)
- Development of analysis case matrix
- Software verification and benchmarking
- Validation planning

Work Status
Software Development

- The status of the new FEACrack software modules by Quest Reliability, LLC is as follows:
  - Growth of surface crack with custom profile (including with nodal repositioning routine): *Issued*
  - Apply user-defined temperature distribution for the cylinder model with a text box "macro" input: *Issued*
  - Implement rigid surface contact for crack face closure in the quarter symmetric cylinder: *Issued*
  - Add custom 360° surface circ crack to mesh generator with custom crack growth in the fatigue growth module: *Issued*
  - Implement fatigue crack growth for custom crack front profile for through-wall crack (<360° on ID & 360° on ID): *In progress*
  - New nozzle-to-safe-end geometry to facilitate placing crack into FEA WRS model: *May timeframe*
- See presentation by Greg Thorwald of Quest Reliability, LLC for discussion of FEACrack software extensions

QUEST RELIABILITY
Asset Longevity | Plant Performance

New and Future Features in FEACrack



Greg Thorwald, Ph.D.

303-415-1475

Outline – FEACrack Features

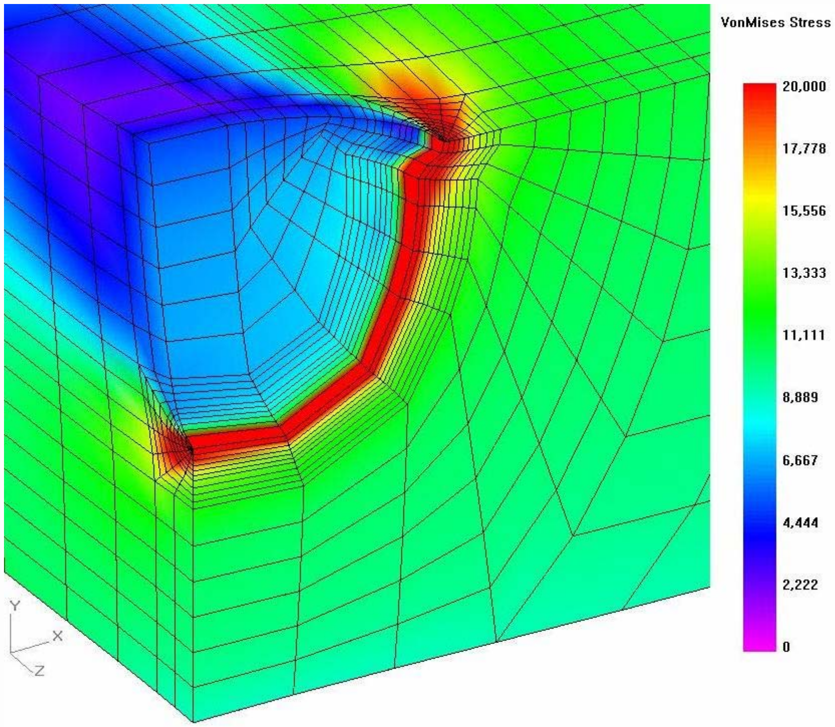
Recently Developed

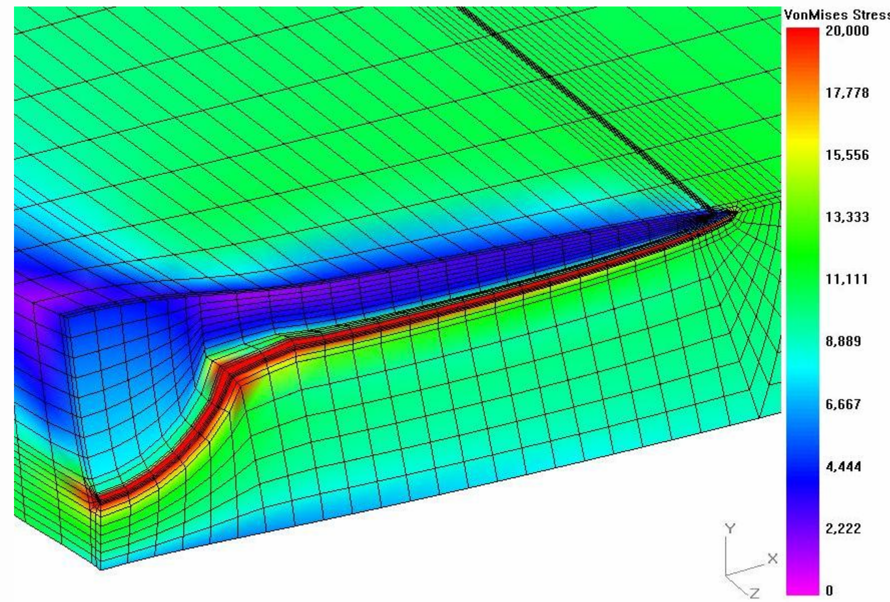
- Custom surface crack
- Ansys macro text, input temperature gradient
- Custom 360º crack
- Node redistribution, fatigue analysis

Future Development

- Complex custom crack
- Update custom through-wall crack
- Nozzle to safe end geometry

Custom Surface Crack





- Enter all crack front node coordinates
- Any number of nodes, arbitrary spacing
- All nodes updated during fatigue analysis

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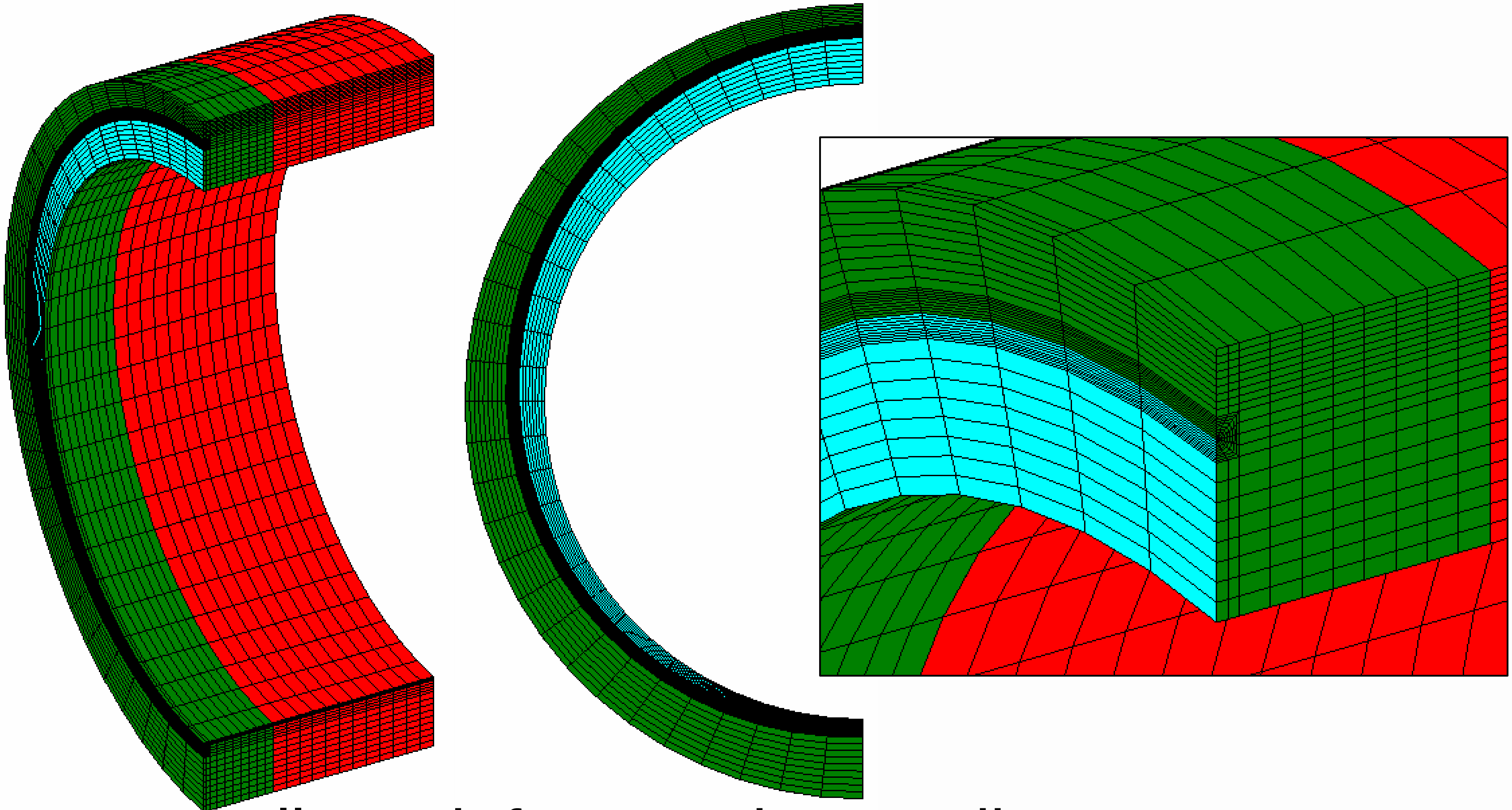
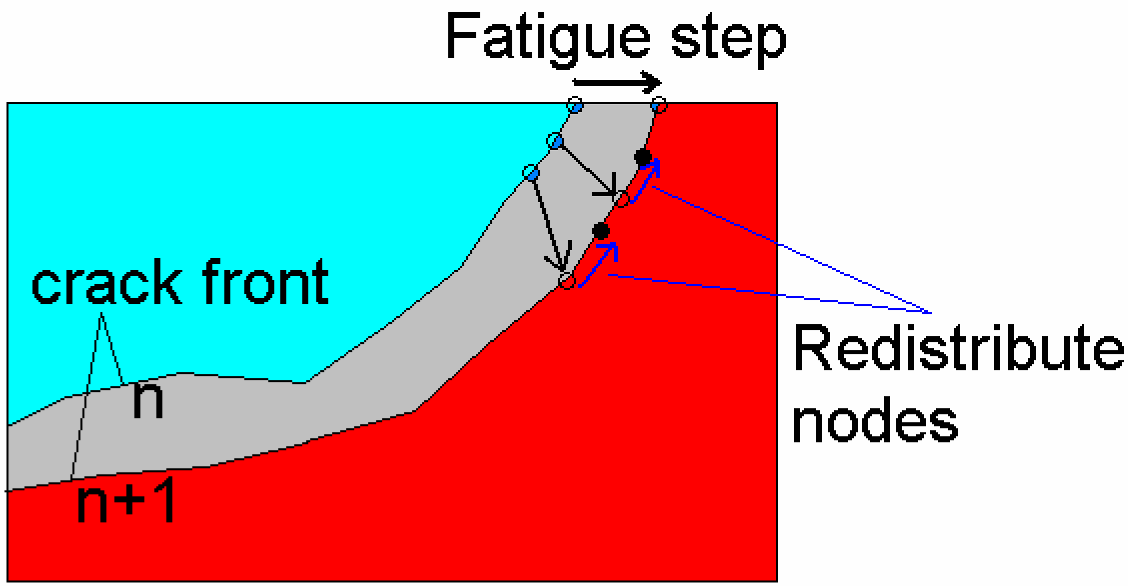
QUEST RELIABILITY

Custom 360º Crack



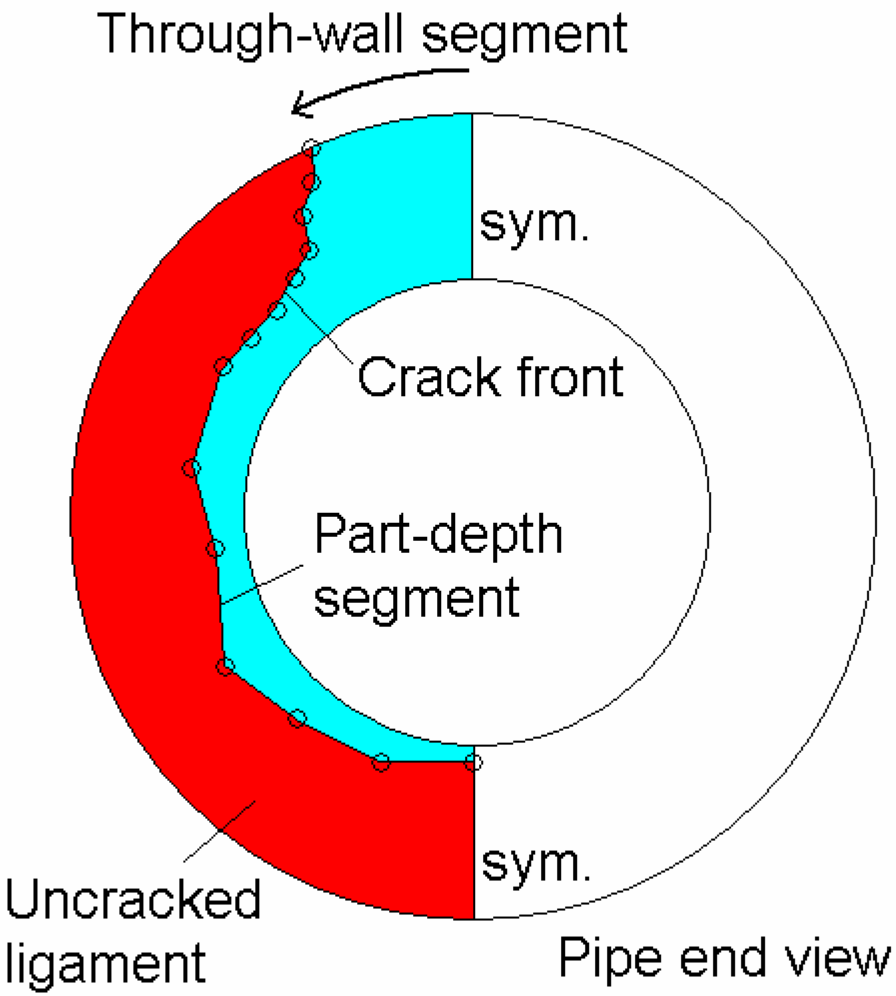
- Enter all crack front node coordinates
  - Any number of nodes, arbitrary spacing
  - All nodes updated during fatigue analysis

Node Redistribution



- An option for fatigue analysis
  - helps avoid numerical problems at the crack tip
- Nodes shift downward along the crack front
- Relocate nodes on updated crack front to preserve the relative node spacing

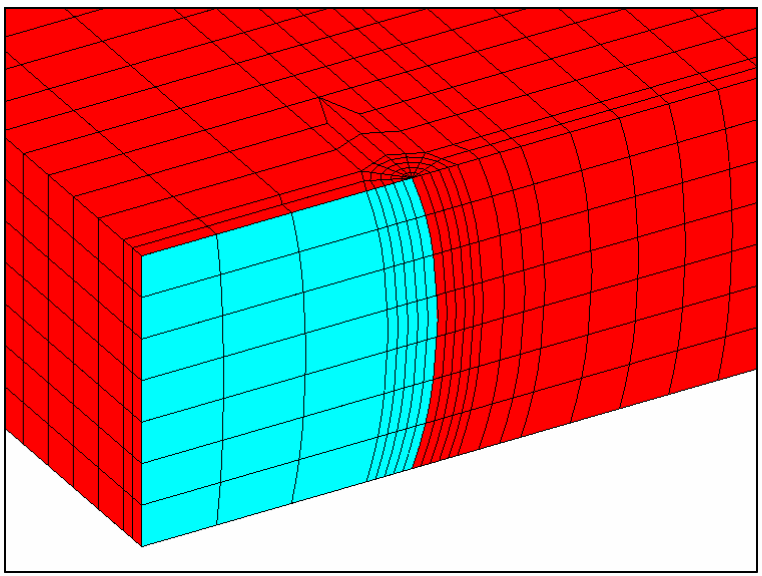
Complex Custom Crack



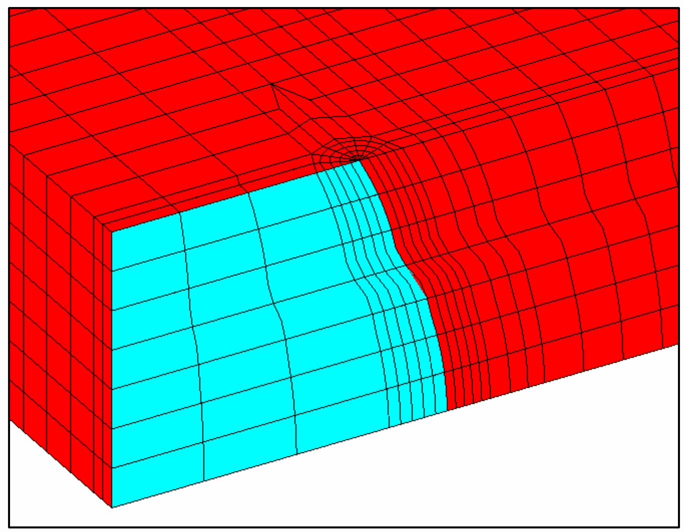
- Through-wall crack shape at the OD crack tip
- Crack front curves to a part-depth crack along pipe ID
- Use custom crack coordinates for all crack front nodes
- Quarter symmetric model

Custom Through-Wall Crack

- Custom through-wall crack is available
- Test and update for custom crack fatigue analysis
  - Update all crack front nodes during fatigue
  - Slanted profile to continue fatigue analysis from surface crack results



Thumbnail Profile



Slanted Profile

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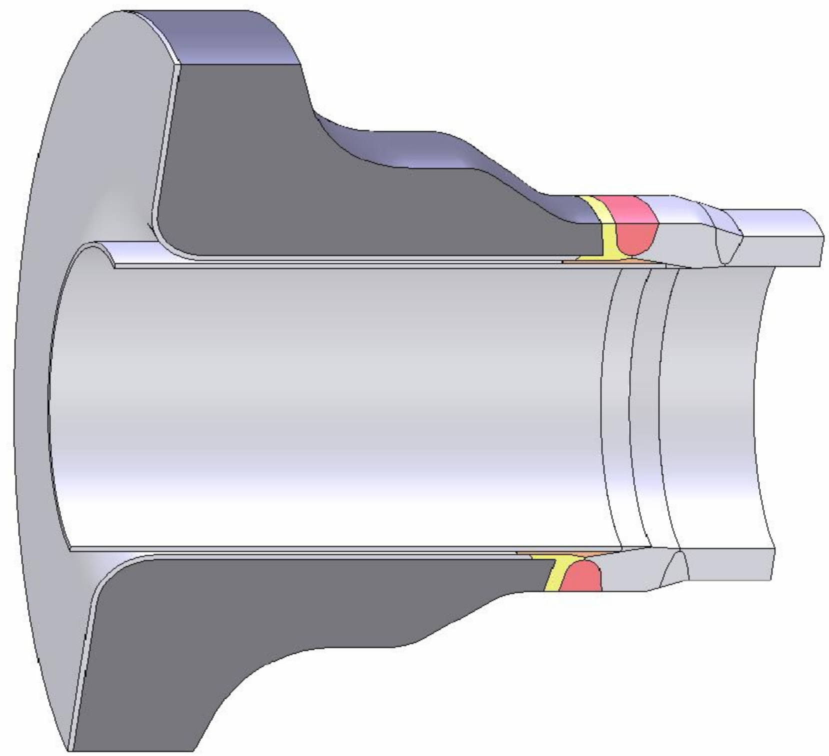
New Nozzle Geometry

Nozzle-to-safe-end geometry

- Add to FEACrack geometry library
- Automatically create the crack mesh in the nozzle geometry
- Allow automated parametric analysis



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

April 4, 2007, NRC Letter
Comments on Crack Growth Calculation

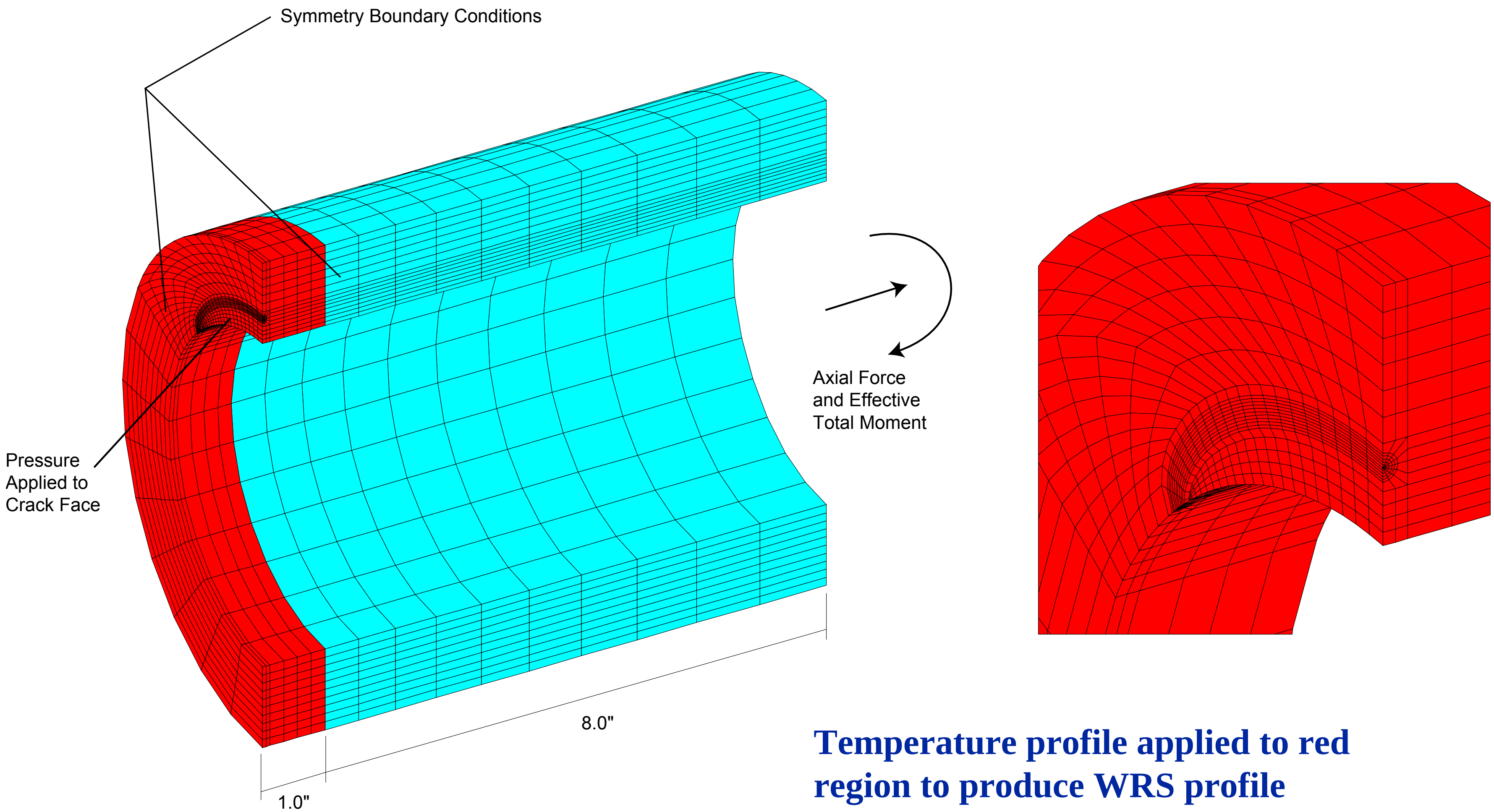
- *Comment #1.* The industry incremented the crack growth in the analyses based on constant increment of crack growth in the length direction for the majority of the analyses. This constraint caused the times for the crack extension at the surface and depth to be different. Even though these differences are small, over the entire time period the sum of the differences could be substantial. This difference could bring into question the validity of the crack shape at leakage. Growing the crack along the crack front by a constant time increment seems more logical and more representative of the crack growth physical characteristics. We suggest further investigation into the crack increment calculation is warranted.
- *Response.* As discussed with the NRC on the April 9 conference call, this comment represents a misunderstanding of the crack increment calculation method. A standard fully explicit time stepping procedure is applied. In order to investigate the adequacy of the time step size in the Phase I calculation, an improved estimate of the elapsed time was calculated based on the crack growth rates from the stress intensity factor at the beginning and at the end of each time step. In the most recent industry work, we are explicitly decreasing the time step size to confirm time and crack profile convergence.

April 4, 2007, NRC Letter
Comments on Crack Growth Calculation

- *Comment #2.* In Figure 11 of industry's Phase I calculations on the evolution of the stress intensity factors, a discontinuity occurred after the second increment of crack growth, and appears to occur at the same stress intensity for each of the remaining steps. Industry's response to a question on this observation during the March 20, 2007, teleconference was unclear, but industry indicated they believed the response was real. We suggest further investigation into the mesh density or the crack increment calculation is warranted. It is recognized that this effect is probably secondary in nature.
- *Response.* The observed behavior is a real effect in terms of the stress intensity factor being locally high where the crack front profile is not smooth. In recent work, DEI has concluded that this behavior observed in the draft Phase I calculation was an artifact of the crack growth increment size. Reducing the crack increment along the ID circumference results in a fully behaved stress intensity factor profile. The new results for the Phase I calculation inputs confirm that this issue in fact had a small effect on the crack profile at the point of through-wall penetration.

Refined Phase I Calc Results

Figure 1: FEA FM Model Using FEACrack / ANSYS



Temperature profile applied to red region to produce WRS profile

Refined Phase I Calc Results

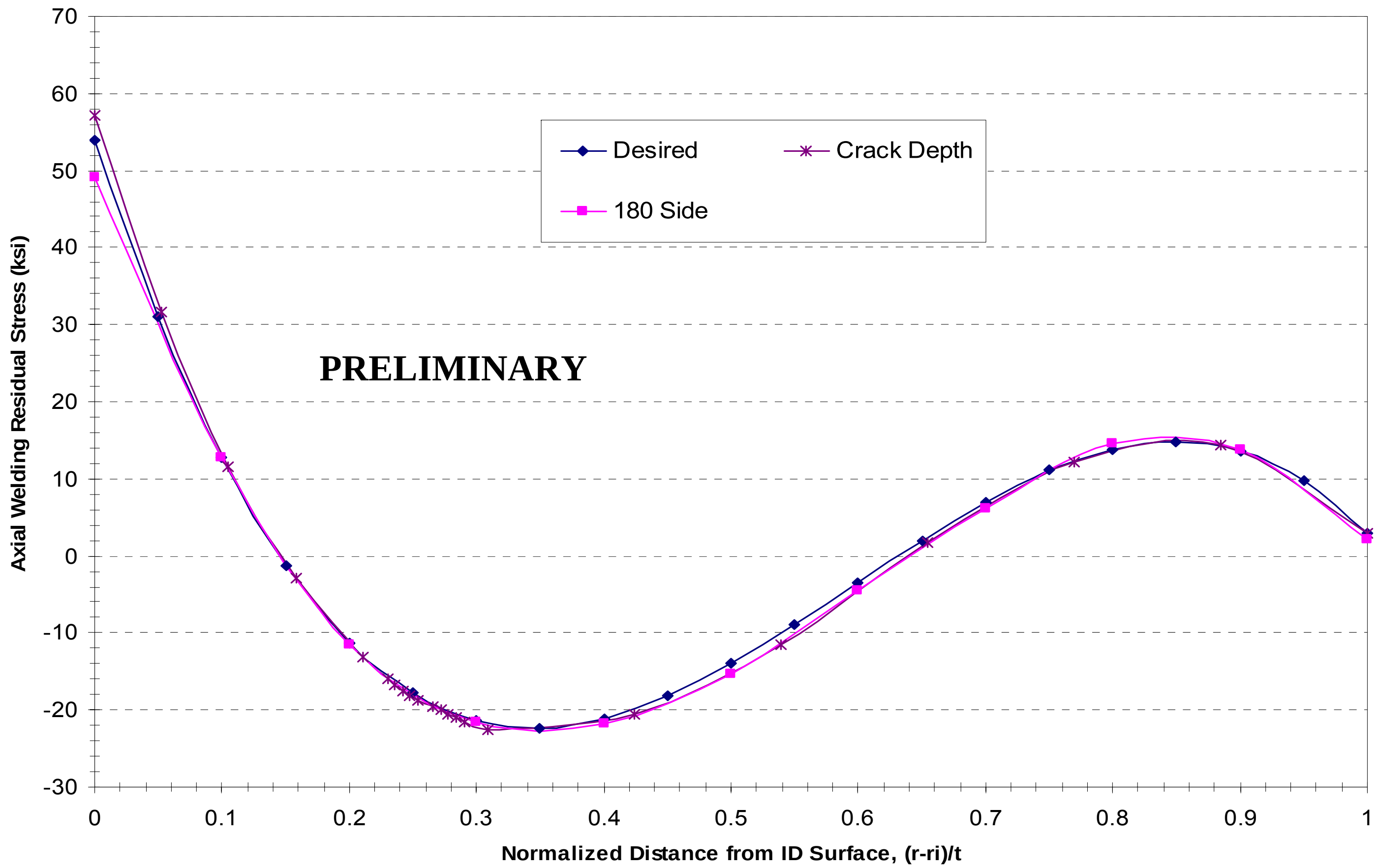
Methodology Adjustments

- Mesh refinement changes to shift additional nodes at surface region of crack front
- Temperature loading adjustments and mesh refinement changes to improve through-wall stress distribution
- Crack shape study to develop more "natural" crack shape for initial size parameters
- Reduced crack growth / time increment
  - 3X previous number of steps
  - Maintains flaw shape stability during automatic crack growth
  - Use new arbitrary depth ID circ flaw capability when flaw reaches 360°
  - Ligament between crack ends conservatively eliminated instantaneously as partial-arc crack approaches 360°

Refined Phase I Calc Results

Figure 2: WRS Distribution Assumption Based on ASME Data

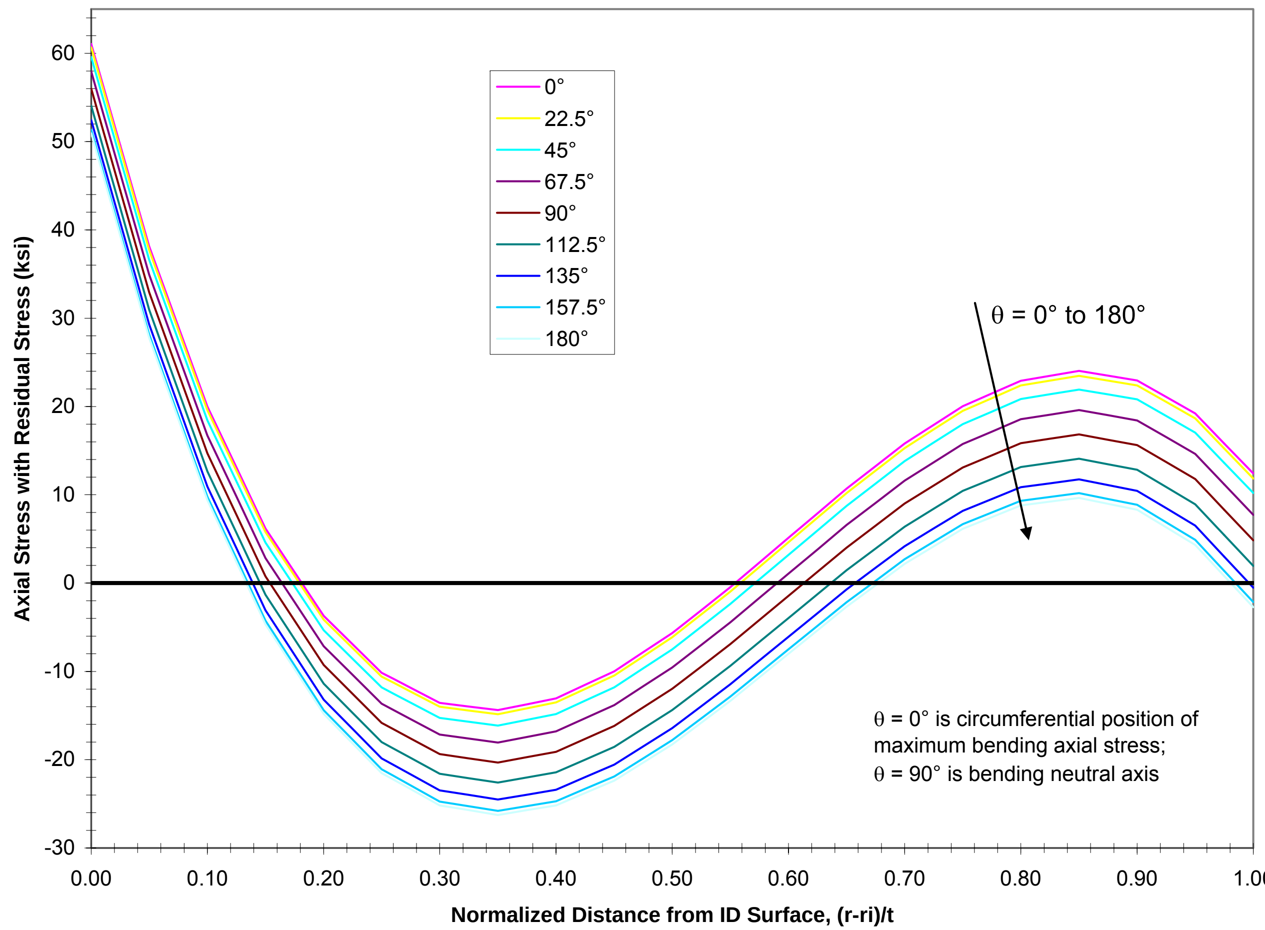
- Temperature profile improved to match desired curve



Refined Phase I Calc Results

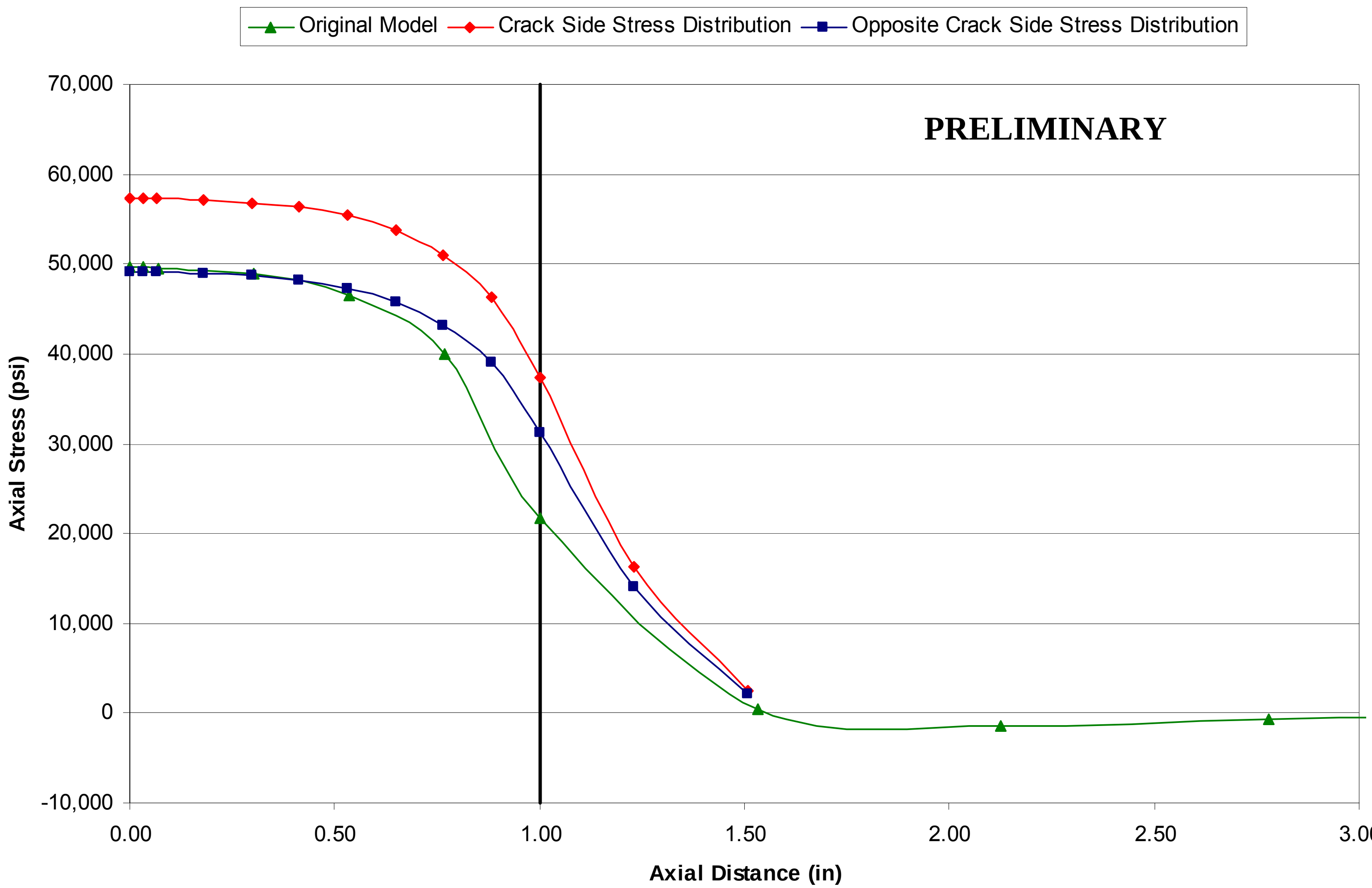
Figure 3: Assumed Axial Stress Loading for Crack Growth

- Identical load case assumed as previous
  - Endcap pressure load
  - Dead weight force and moment
  - Pipe thermal expansion force and moment
  - Assumed WRS distribution
- Crack face pressure also applied



Refined Phase I Calc Results

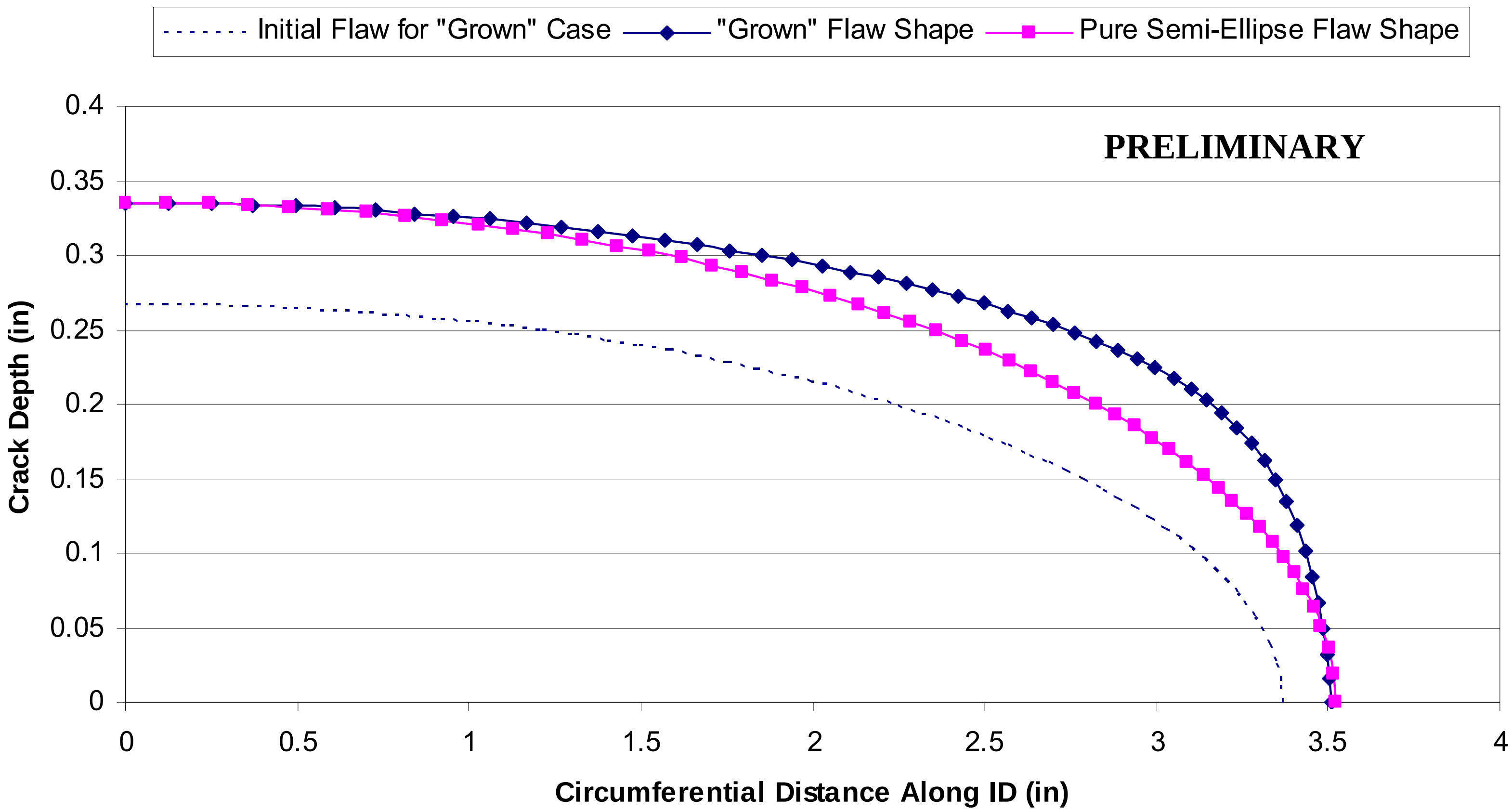
Figure 4: Axial Extent of Imposed Thermal Stress Simulating WRS



Refined Phase I Calc Results

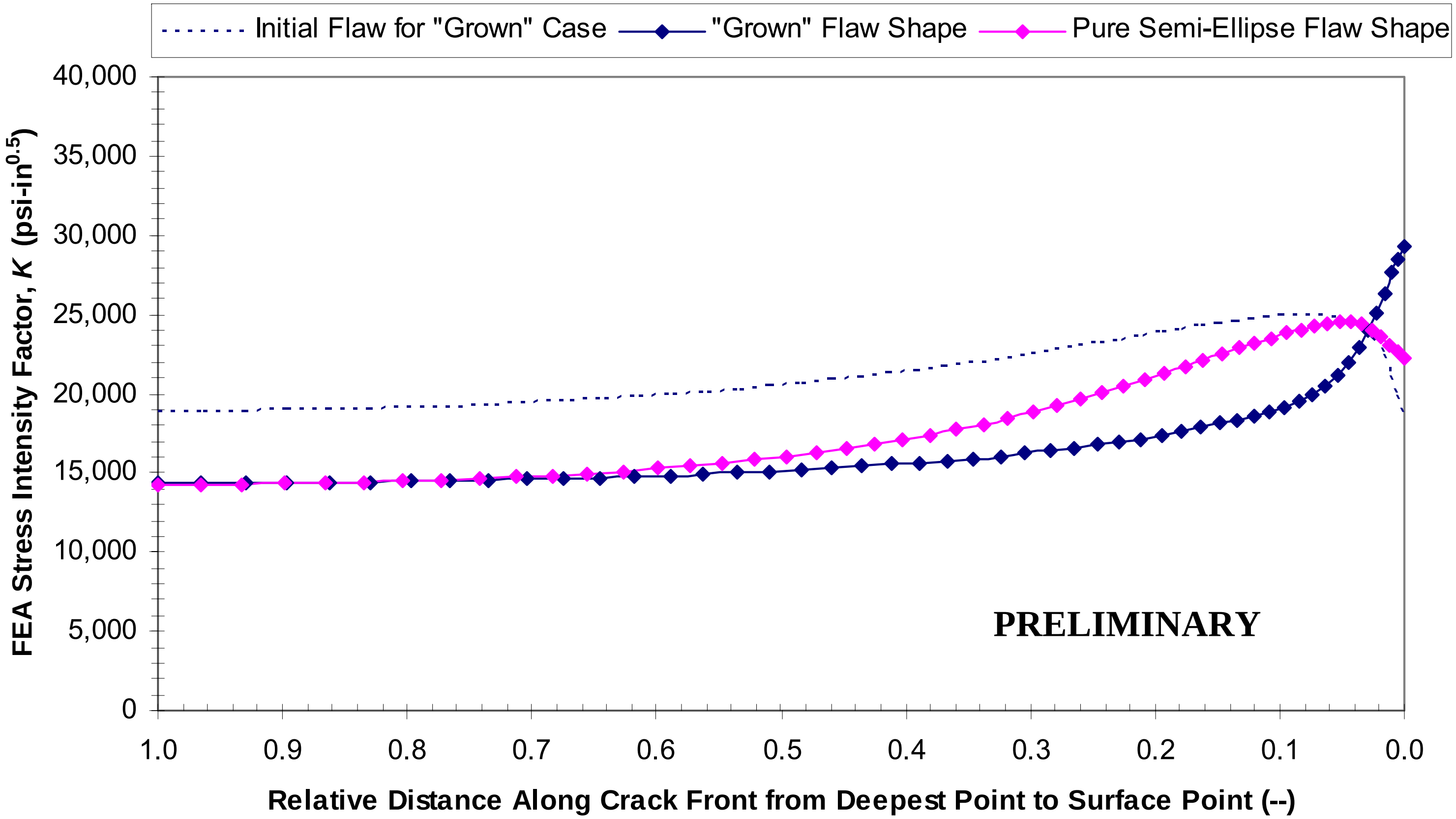
Methodology Adjustments

- "Natural" shape developed by growing semi-ellipse shape out to desired depth and length



Refined Phase I Calc Results
Methodology Adjustments (cont'd)

- Additional refinement and "natural" shape yield smoother crack tip SIF profile



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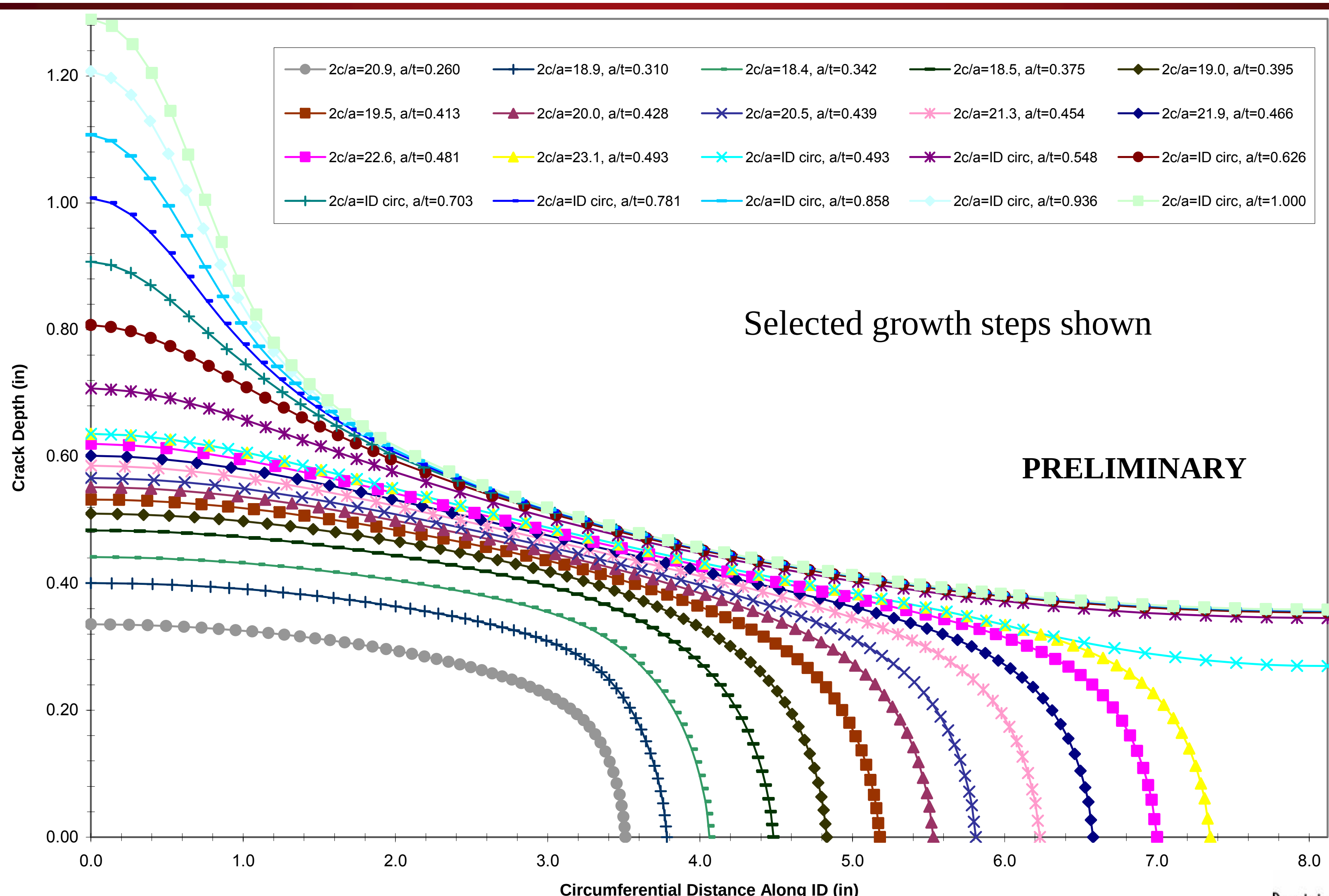
Refined Phase I Calc Results

Figure 7: Growth Progression in Flat Plane



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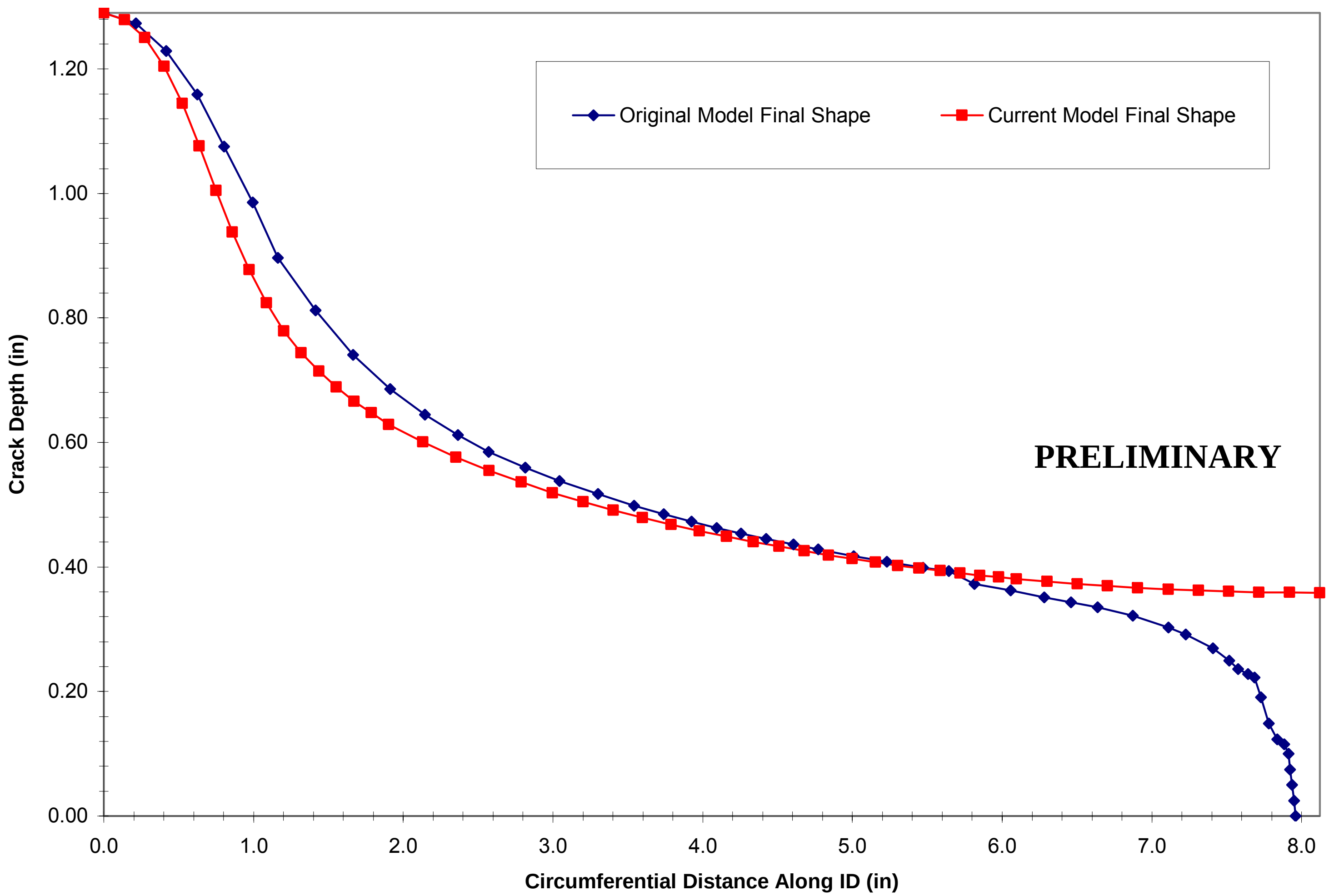
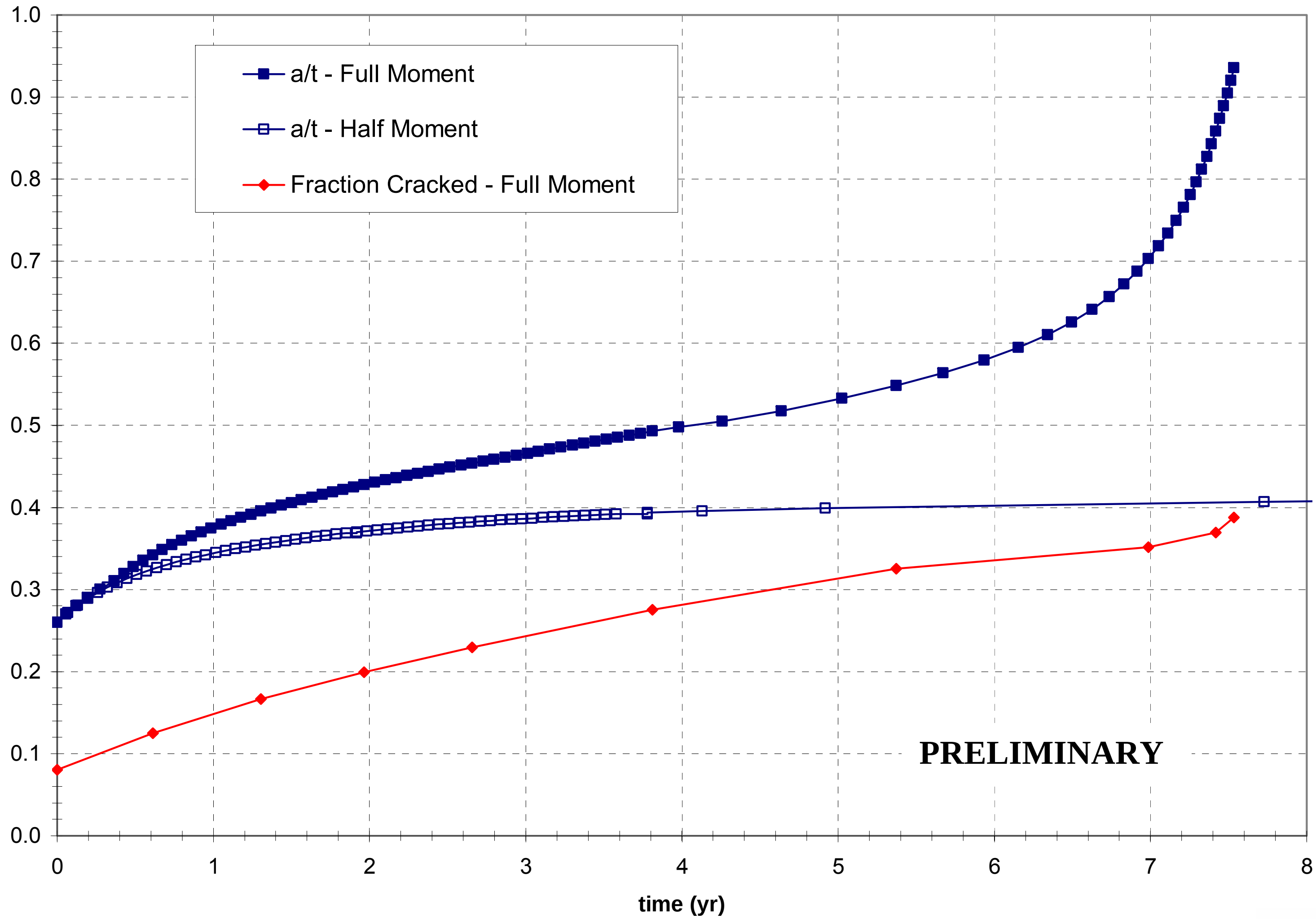
Refined Phase I Calc Results
Profile Comparison vs. Draft Phase 1 Result



Refined Phase I Calc Results

Figure 9: Crack Depth and Area Development



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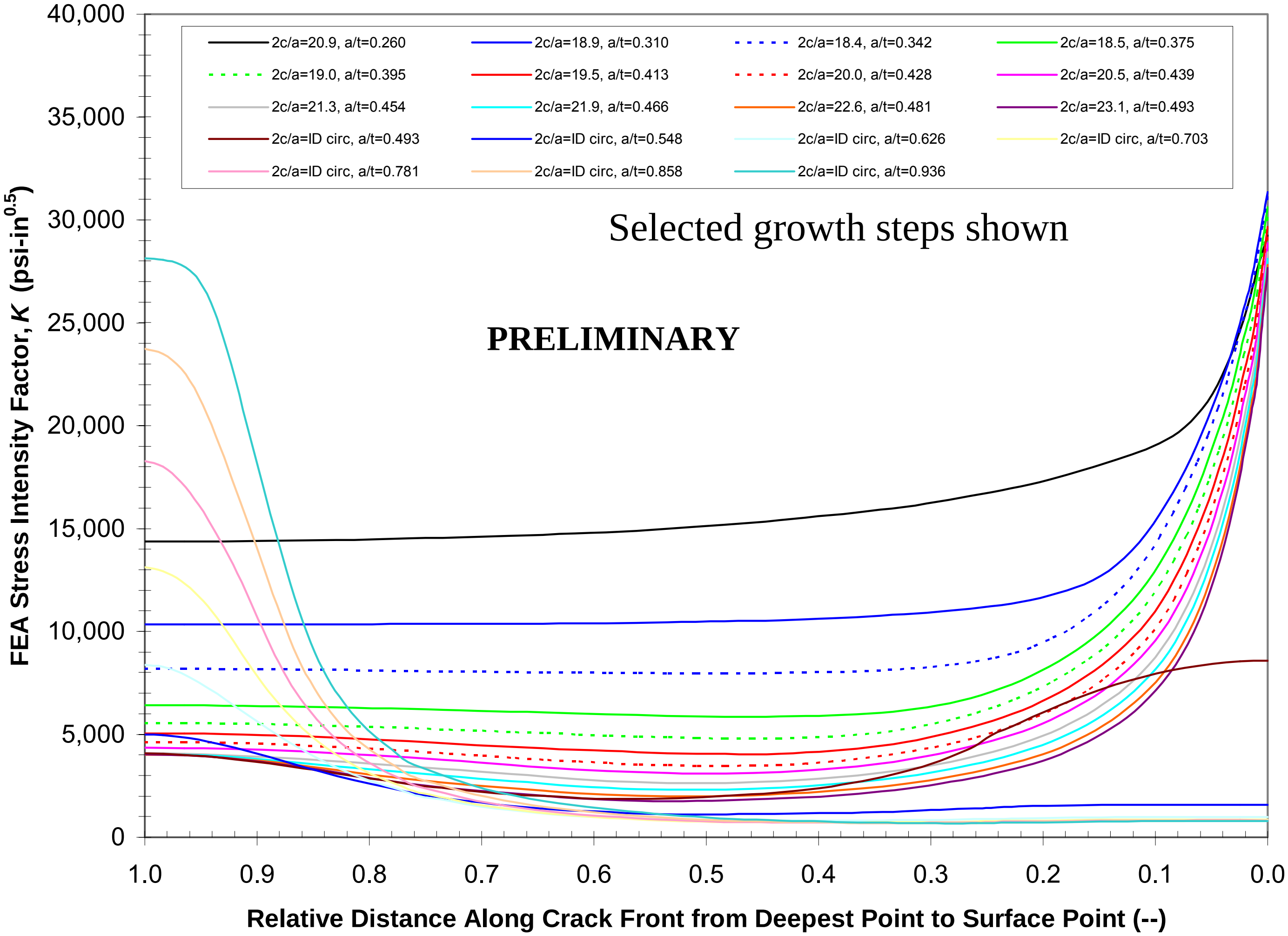
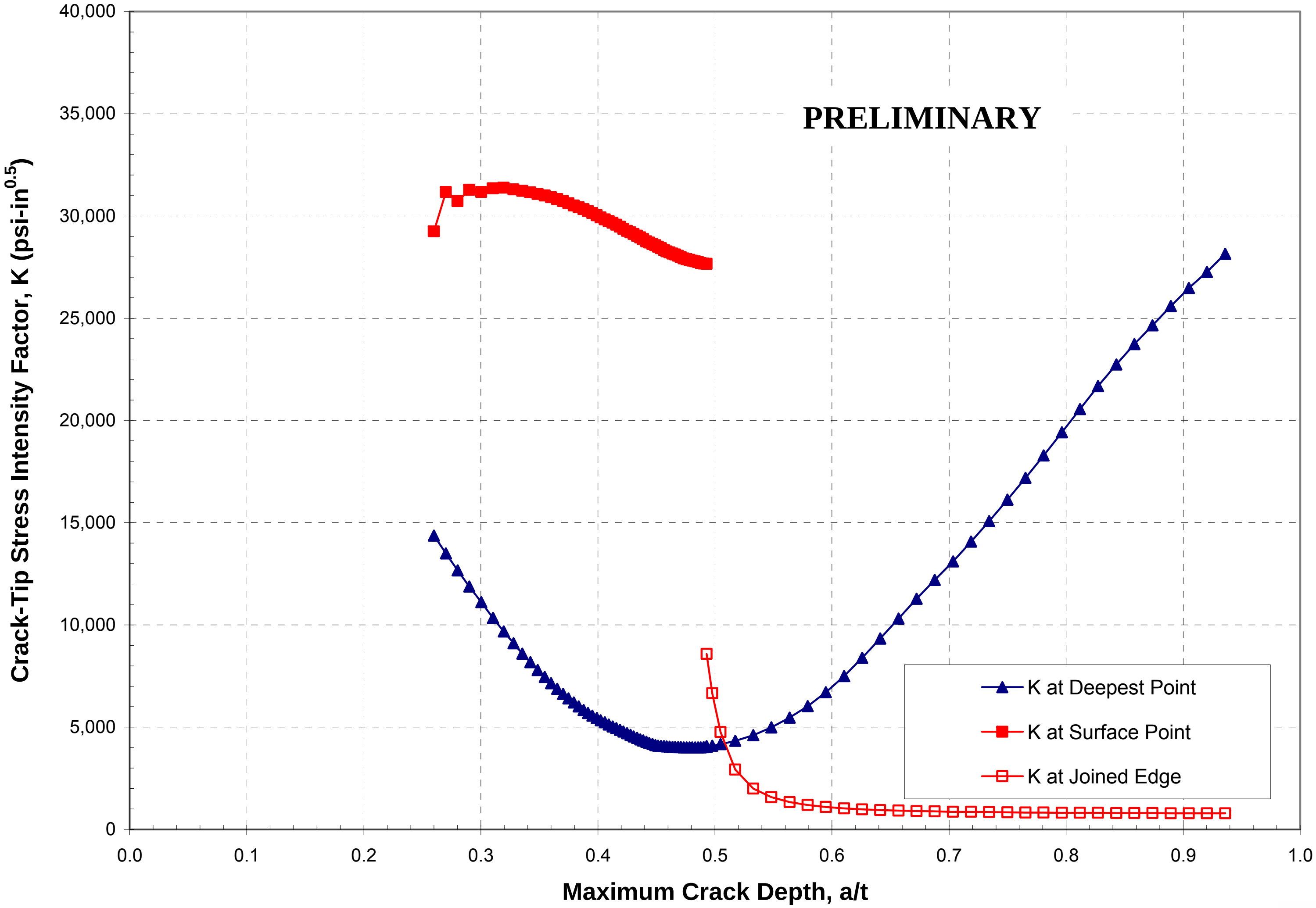
Refined Phase I Calc Results
Figure 11: SIF Along Crack Front



Refined Phase I Calc Results

Figure 12: SIF at Deepest and Surface Points vs. Depth



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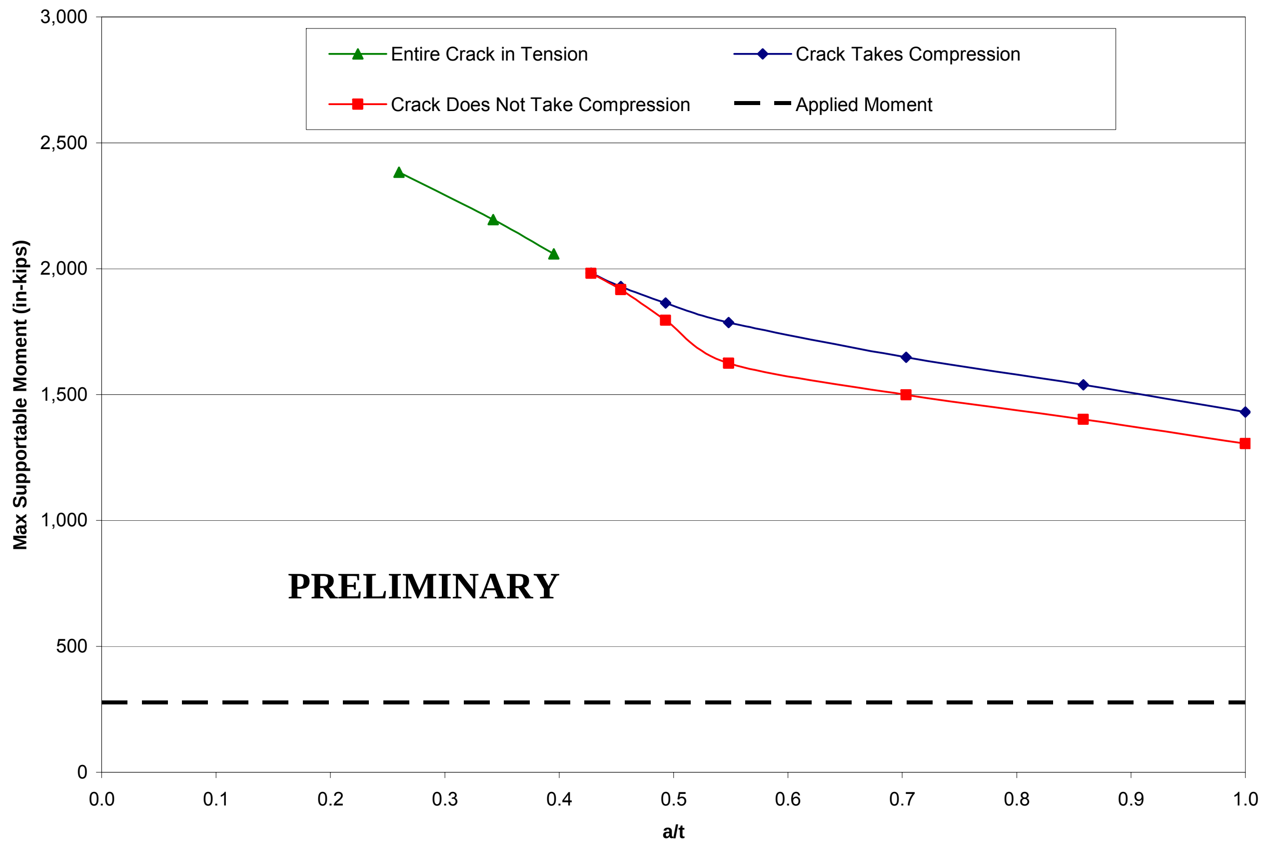
Refined Phase I Calc Results

Figure 14: Crack Stability – Supportable Moment

- Supportable moment based on standard thin-wall NSC model for arbitrary circumferential crack profile (Rahman and Wilkowski, 1998)



Refined Phase I Calc Results
Summary

- Through-wall flaw reached after approximately 7.5 years
  – Increase in growth time due to refined time step and other refinements
- Net section collapse moment for final flaw shape is 1300 in-kips vs. 275 in-kips load (4.7× greater)
  – Based on conservative case in which crack face does not take compression

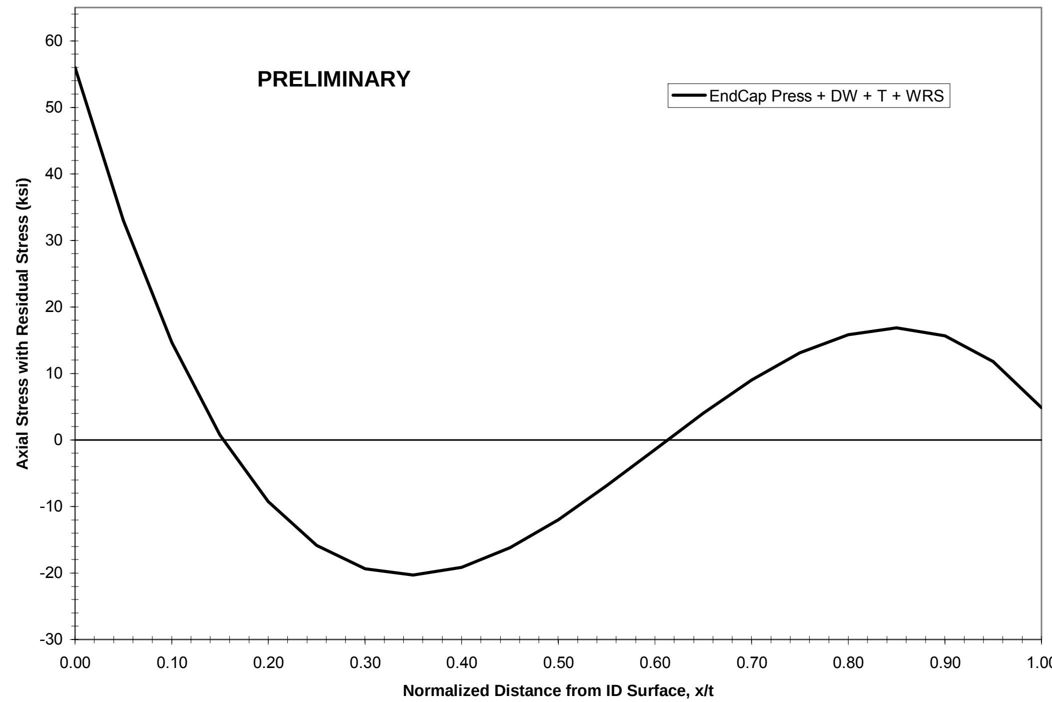
April 4, 2007, NRC Letter
Comments on Crack Growth Calculation

- *Comment #3.* A significant result from these analyses was that the surface crack grew to 360 degrees before becoming through-wall. This effect was driven by the higher residual stresses at the inside diameter (ID) surface. In addition, the shape of the final defect at the location of maximum stress was highly driven by the magnitude of the bending stress relative to the ID welding residual stress. For similar residual stresses with lower bending moments, a critical 360-degree surface crack is likely to occur. Industry needs to address this issue in the analysis matrix for Phase II.
- *Response.* As discussed in the draft Phase I calculation note, the growth to a 360° degree surface flaw results from the somewhat higher stress intensity factors along the surface associated with the crack shape in the ID surface neighborhood, compared to the results for a semi-elliptical flaw shape assumption. As has been discussed since the beginning of the project, the magnitude of the bending stress is expected to be a critical modeling parameter. Phase II was planned to include investigation of the effect of bending moment load based on the full range of piping moment loads collected for the group of 51 subject welds. Contrary to the statement regarding the likelihood of critical 360° surface cracks, recent work indicates that the surface crack is likely to arrest or greatly slow in growth without reaching critical crack size given lower bending moments and similar residual stresses (see following slides).

Crack Growth with Zero Moment

Axisymmetric Results for WC Relief Nozzle with 360° Flaw

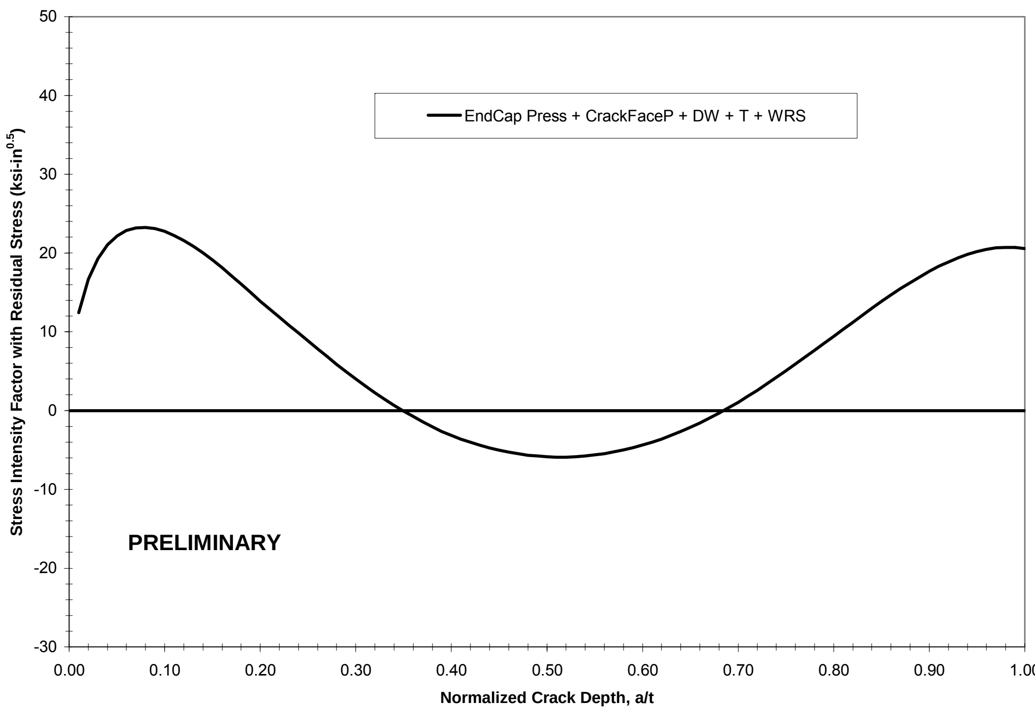
- Assumed axisymmetric stress profile at right
- Endcap pressure based on ID at DM weld
- Dead weight axial force included
- Normal thermal axial force included
- WRS profile of Phase 1 calculation also assumed



Crack Growth with Zero Moment

Axisymmetric Results for WC Relief Nozzle with 360° Flaw

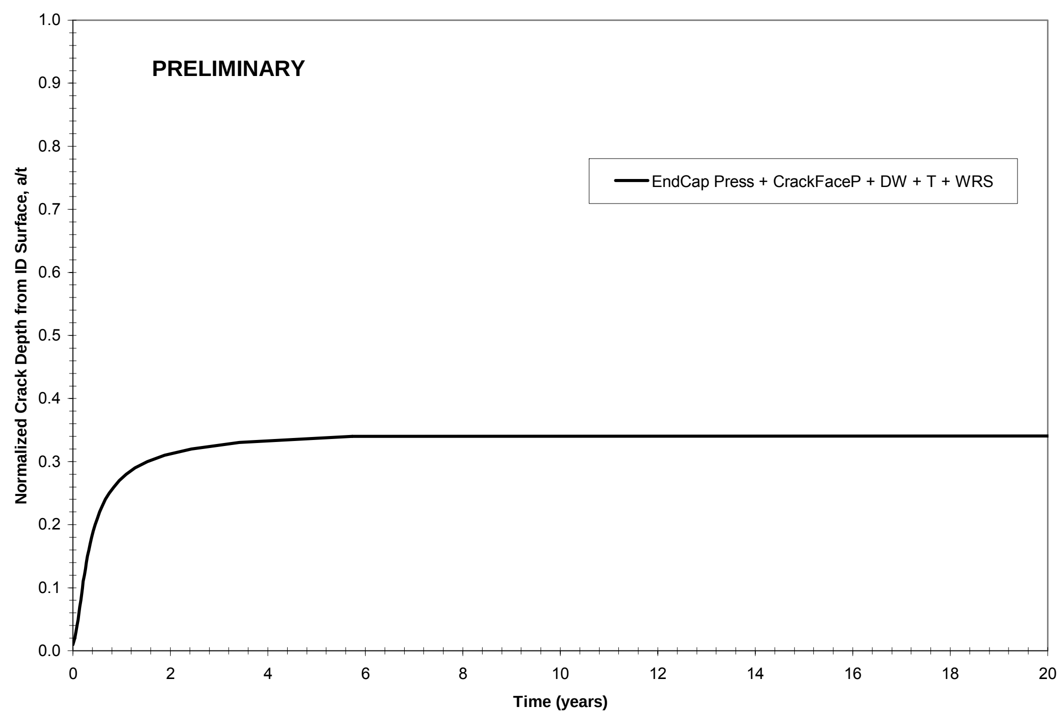
- SIF per WRC Bulletin solution for fully axisymmetric stress field (cubic dependence on radial coordinate) and 360° uniform depth circumferential surface crack
- WRC Bulletin includes influence coefficients for case of $R_i/t = 2$, so no extrapolation needed
- Crack face pressure applied via superposition



Crack Growth with Zero Moment

Axisymmetric Results for WC Relief Nozzle with 360° Flaw

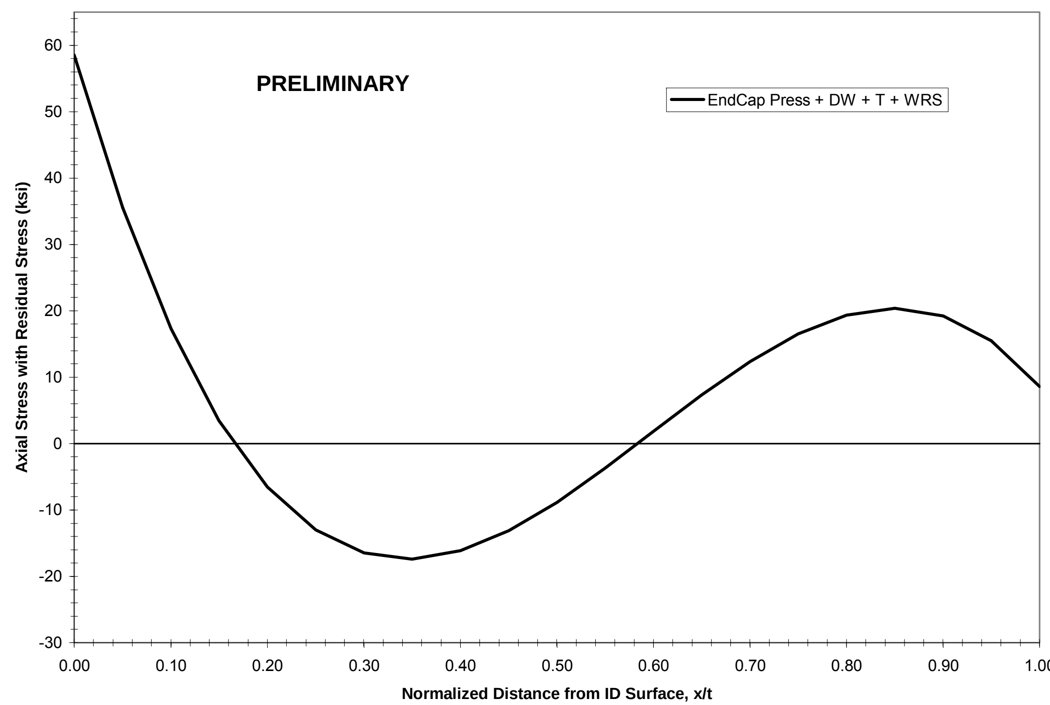
- Crack depth vs. time based on integration of MRP-115 CGR equation at 650°F
- Crack arrest predicted at depth of about *a/t* = 0.35
- Conclusion is that without piping moment load, assumed WRS profile results in arrested (and stable) part-depth crack for the relief nozzle case investigated, regardless of initial crack aspect ratio



Crack Growth with "Axisymmetric" Moment

Axisymmetric Results for WC Relief Nozzle with 360° Flaw

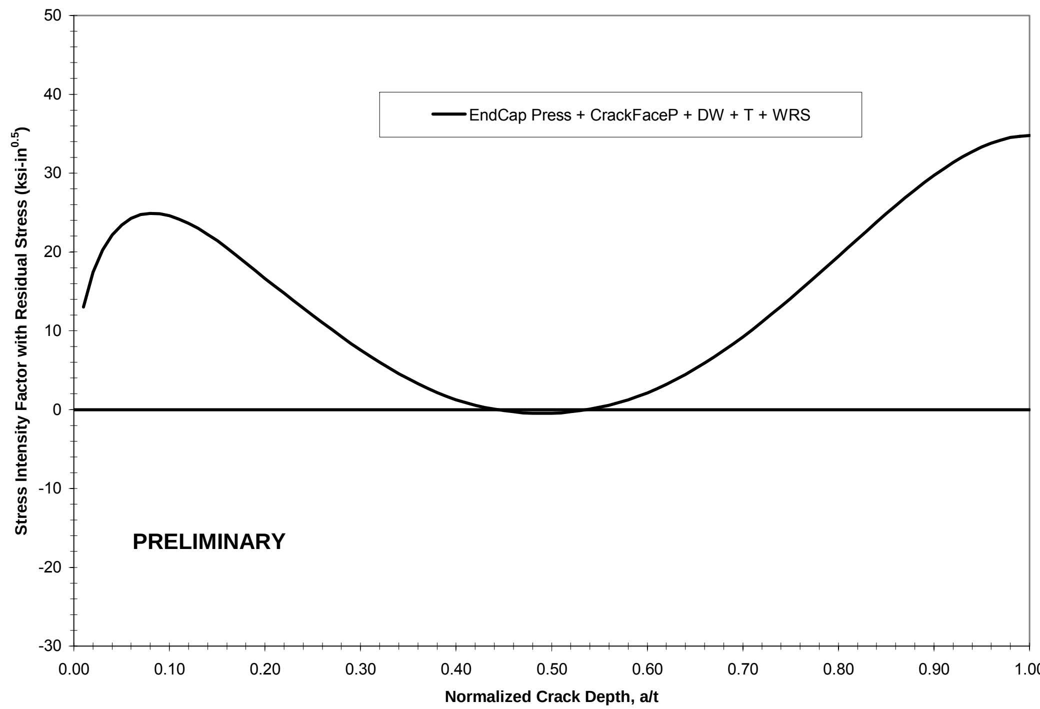
- Assumed axisymmetric stress profile at right
- Axisymmetric linear stress profile *Mr/I* added to previous zero moment case
- M taken as half base case moment of 275 in-kips
- This hypothetical axisymmetric case bounds capability of moment to drive crack through-wall for assumed WRS profile



Crack Growth with "Axisymmetric" Moment

Axisymmetric Results for WC Relief Nozzle with 360° Flaw

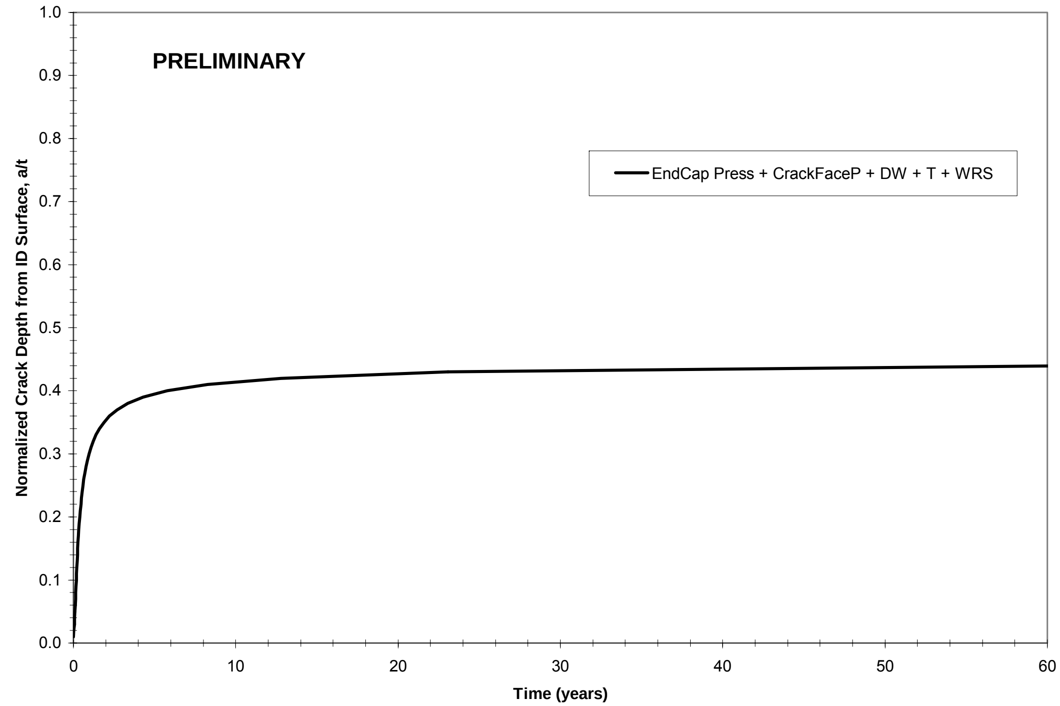
- Same SIF solution procedure as before using WRC Bulletin
- Crack face pressure applied via superposition



Crack Growth with "Axisymmetric" Moment

Axisymmetric Results for WC Relief Nozzle with 360° Flaw

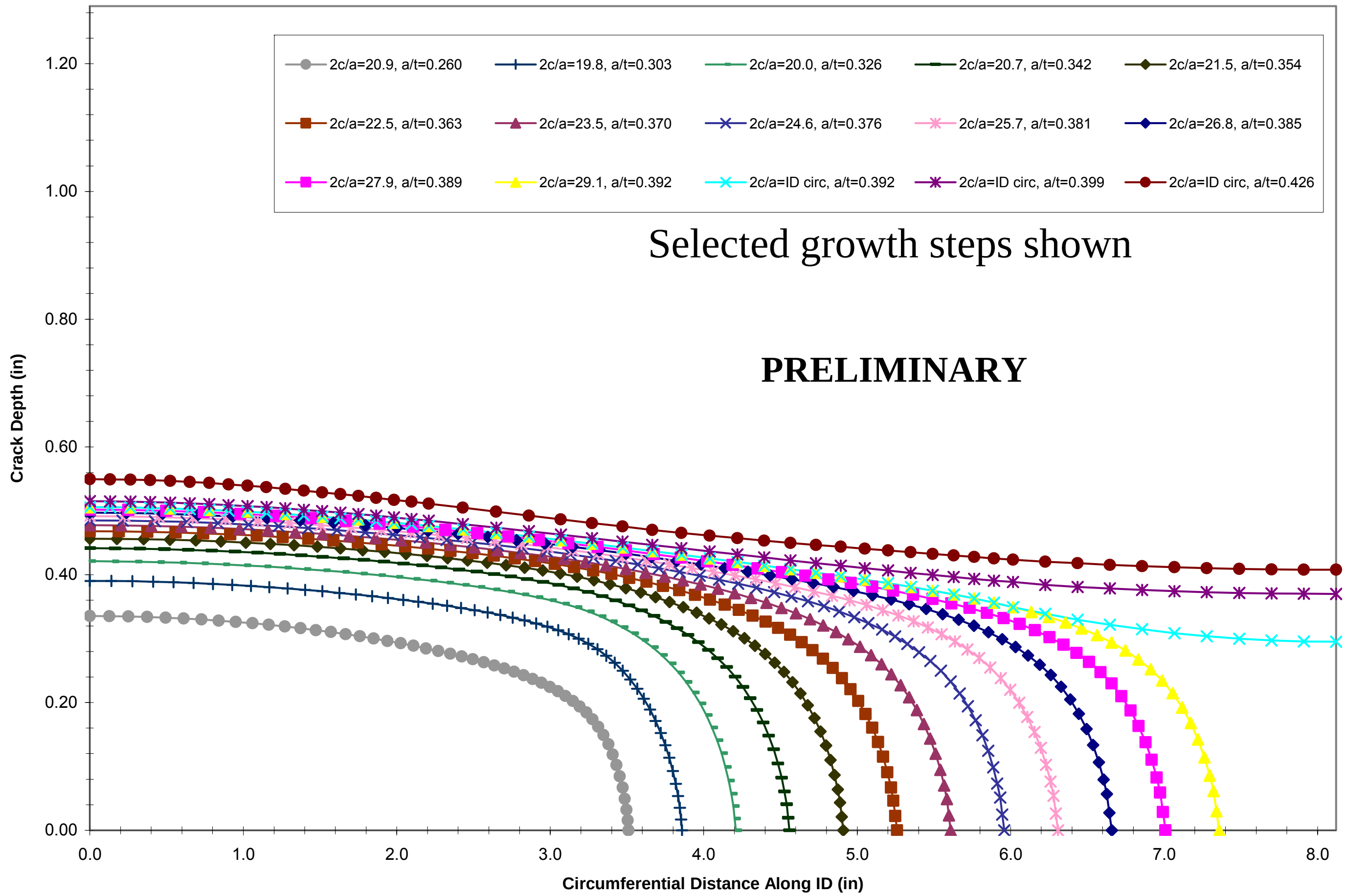
- Crack depth vs. time based on integration of MRP-115 CGR equation at 650°F
- Crack arrest predicted at depth of about *a*/*t* = 0.45
- Conclusion is that even with half base case moment of 275 in-kips, assumed WRS profile results in arrested (and stable) part-depth crack for the relief nozzle case investigated, regardless of initial crack aspect ratio



Crack Growth with Reduced Moment

FEA Results for WC Relief Nozzle with 21:1 Flaw

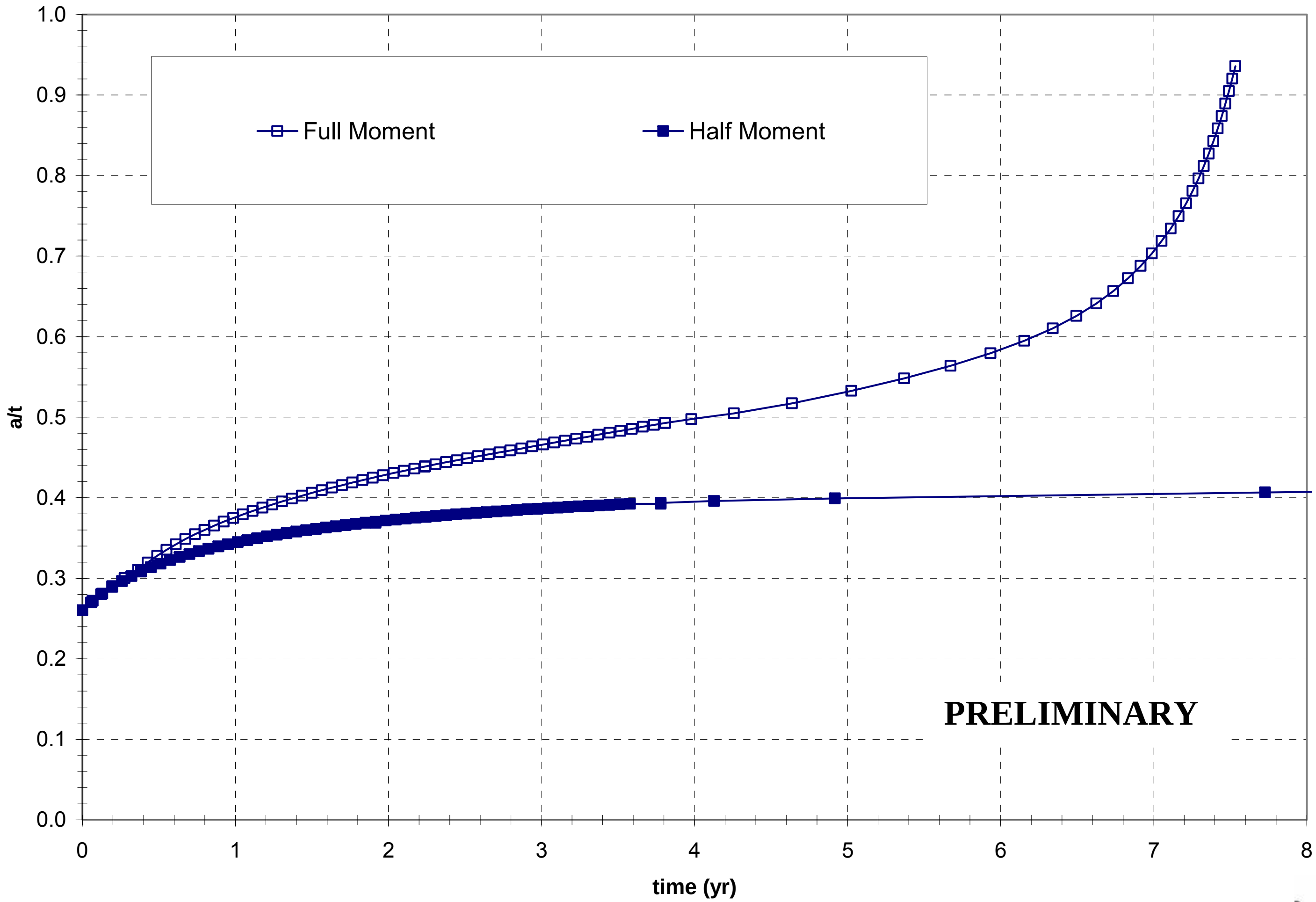
- Growth progression in flat plane for case of half previously assumed piping moment



Crack Growth with Reduced Moment

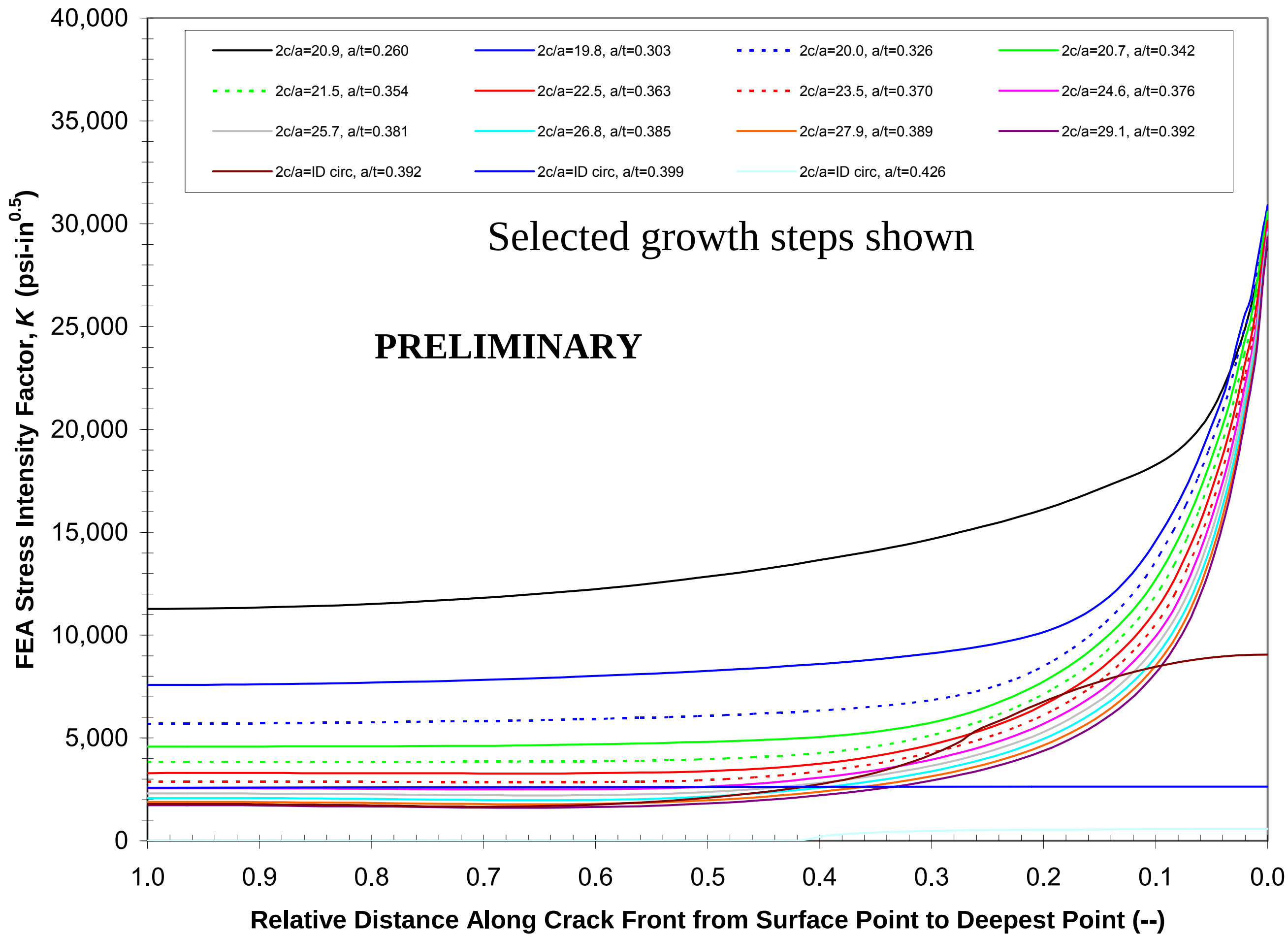
FEA Results for WC Relief Nozzle with 21:1 Flaw

- Crack depth development for case of half previously assumed piping moment



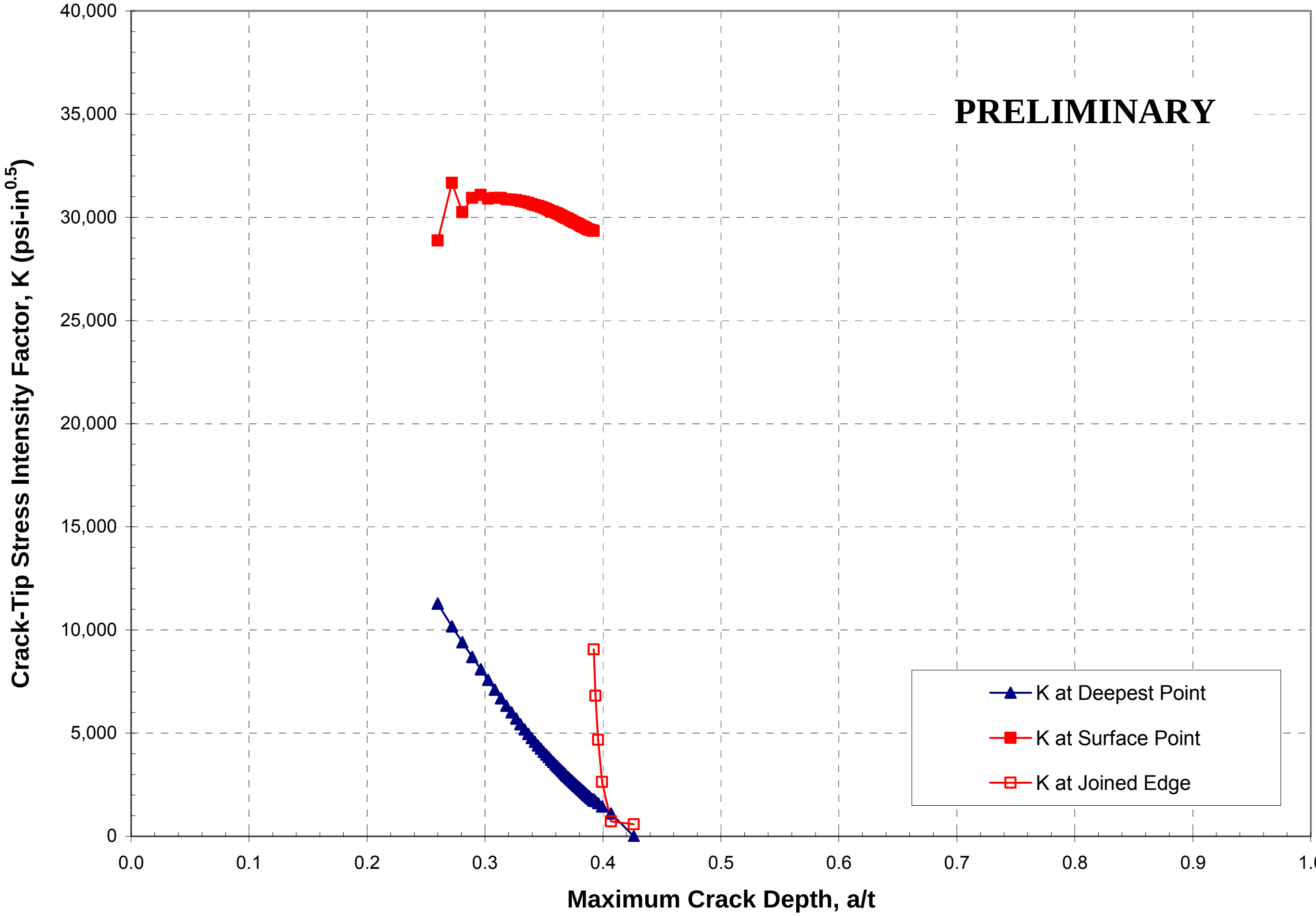
Crack Growth with Reduced Moment
FEA Results for WC Relief Nozzle with 21:1 Flaw

- SIF along crack front for case of half previously assumed piping moment



Crack Growth with Reduced Moment
FEA Results for WC Relief Nozzle with 21:1 Flaw

- SIF at deepest and surface points vs. depth for case of half previously assumed piping moment



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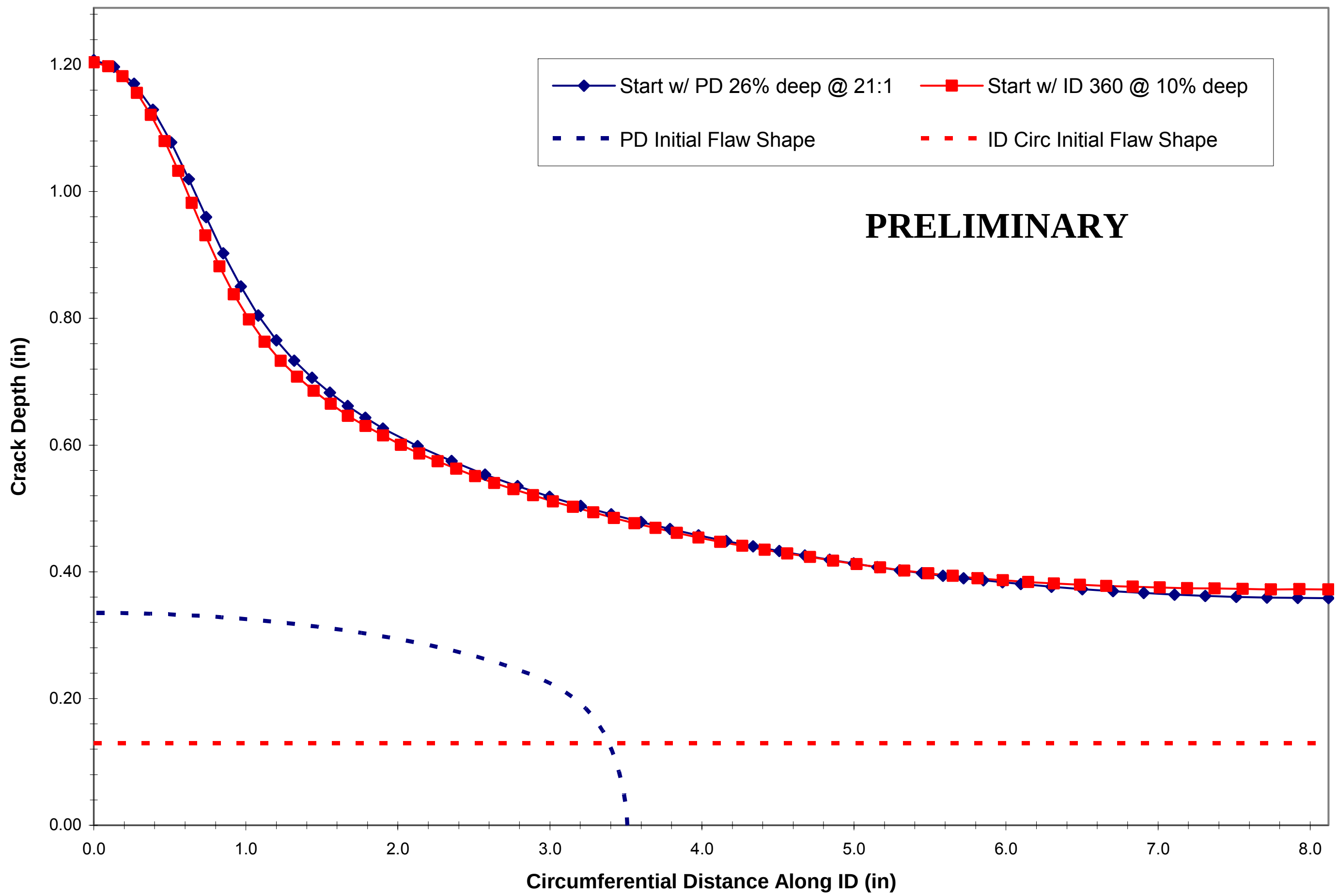
Crack Growth with Full Moment

FEA Results for WC Relief Nozzle with 360° Flaw

- Initial and final flaw shape comparison for partial-arc initial flaw vs. 360° initial flaw



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New FEA Crack Growth Cases
Conclusions

- Smooth crack-tip SIF profiles result from greater mesh refinement at surface and smaller time step increment
  - Starting from "natural" flaw shape does not improve SIF profiles
- Greater time step refinement (with other minor changes) yields time to through-wall of about 7.5 years
- Reduced moment leads to flaw arrest for assumed through-wall stress distribution
- High inside surface stresses lead to no significant difference in crack profile at through-wall penetration for partial-arc and 360° circumferential starting flaws
  - 360° initial flaw @ 10% depth takes 8.4 years to reach same final flaw shape

April 4, 2007, NRC Letter
Comments on Critical Crack Size Calculation

- *Comment #4.* The last comment relates to the calculation of critical crack sizes which affect the calculation for the time to rupture. In the Phase I results, industry used a limit-load analysis with the weld metal flow stress to estimate the critical through-wall crack size; then industry used that cross-sectional cracked area to draw conclusions about the stability of the leaking surface crack. In addition, industry did not evaluate the displacement-controlled stresses in this stability calculation, arguing that these stresses would be relieved by the plasticity and change in compliance due to the large crack. From reviewing past full-scale pipe testing results, it is the NRC staff's view that in conducting critical crack size analyses, industry must address the following concerns.
  - *Comment #4a.* The location of the crack in a dissimilar weld can change the fracture response. If the crack is close to the safe-end then the lower strength of the stainless steel safe-end should be used. If the crack is in the center of the weld or closer to the ferritic nozzle side, the effective flow stress would be slightly higher than using the safe-end strength but much lower than using the weld metal strength properties. Hence, if the location of the crack in the weld is not known, then the conservative assumption is to use the lower safe-end strength properties. This fact is supported by both analyses and experiments.

April 4, 2007, NRC Letter
Comments on Critical Crack Size Calculation (cont'd)

– *Comment #4b.* Elastic-plastic fracture mechanics should be considered since in the NRC analyses, this condition controlled for some crack geometries. For an idealized circumferential through-wall crack as used in industry's failure analysis, the NRC staff's detailed finite element elastic-plastic analyses and pipe tests showed that failure stress would be below that predicted by limit-load analyses even when using the stainless-steel base-metal strength properties in the limit load analysis. For a circumferential surface flaw, the experiments and analyses suggest that limit-load using the lower strength properties would be appropriate. Finally, for a complex or compound crack, i.e., a long surface crack that penetrates the wall thickness for a short length, full-scale pipe tests have shown that the failure stress would be significantly below limit load. This crack shape is similar to the flaw found in the Duane Arnold safe end. The results also indicate that secondary stresses can lead to rapid severance of pipes containing complex cracks. Consequently, there can be significant non-conservatism in the industry's fracture analysis.

April 4, 2007, NRC Letter
Comments on Critical Crack Size Calculation (cont'd)

– *Comment #4c.* For large cracks, especially surface and complex cracks, the plasticity is localized to the area surrounding the crack, and therefore the secondary loads will not be relieved by a change in compliance. If the crack is large enough so that the rest of the pipe system remains elastic, then these secondary stresses will act as a primary stress. If the failure stresses are above yield of the uncracked pipe, there will be a gradual reduction of the importance of secondary stresses, but this is material and pipe-system geometry dependant. This condition may begin to relieve some of these loads, but total relief will not occur until there is large scale plasticity in the uncracked pipe loop. This secondary stress effect on fracture response is consistent with the ASME Section III design rules that offer a warning about Local Overstrain due to a weakened pipe cross section. There are full-scale pipe system tests with different amounts of thermal expansion stress that illustrate this fracture behavior in NUREG reports and technical papers.

April 4, 2007, NRC Letter

Industry Response to Comment #4

- Pete Riccardella of SI to present main response to Comment #4
- Additional response material on next two slides
  - Ductile tearing of thin surface ligaments
  - Nominal stress in adjacent piping

April 4, 2007, NRC Letter

Ductile Tearing of Thin Surface Ligaments

- Section 2.2.1 and Figure 4 of the draft EMC2 technical basis document for critical crack size recommend that a factor be applied for deep surface cracks
- There is an important distinction between a leakage failure (rupture of local ligament between crack tip and OD) and a break failure. All surface cracks will be predicted to have a leakage "failure" as they approach 100% through-wall according to the correction factor approach in Figure 4 of the EMC2 document.
- If the through-wall crack created is stable, then in fact leakage and not a LOCA will result. We must check for thin surface ligaments at the ends of the through-wall section of the final complex crack.
- A second order question is whether any surface ligament tearing during the previous crack growth changes the crack growth pattern significantly versus growth by SCC only. Under the conditions that could produce local ligament ductile tearing, the predicted SCC growth rate will be high, effectively simulating the effect of the surface ligament tearing.

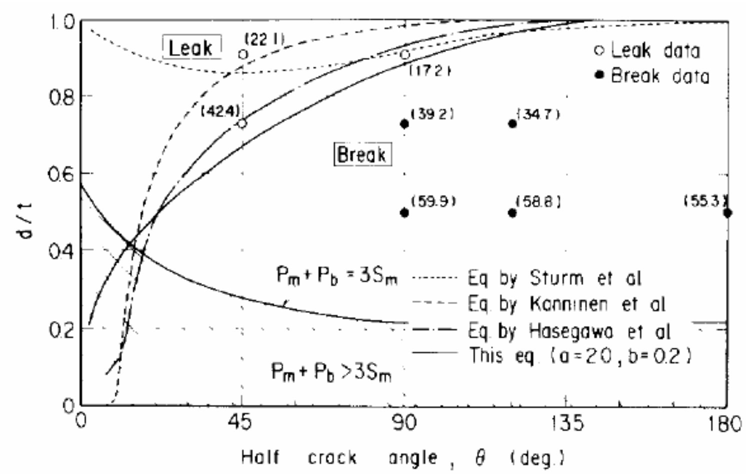


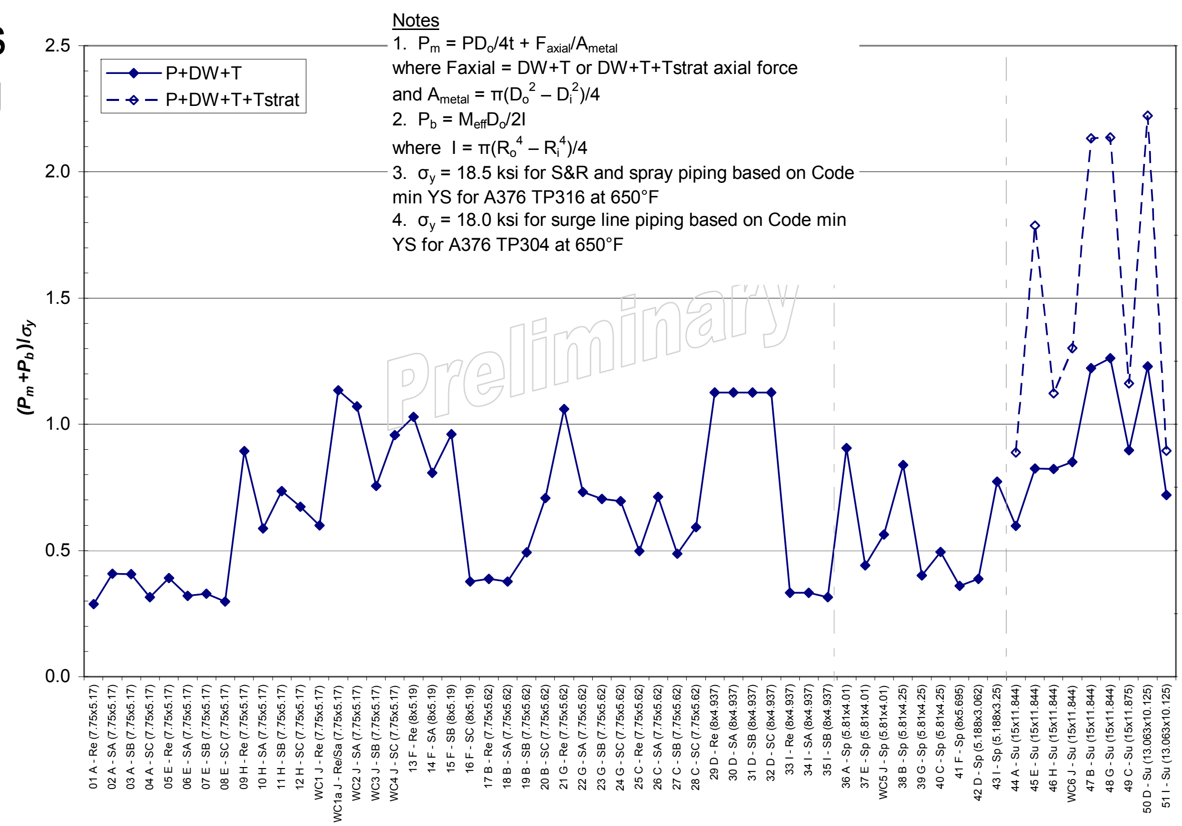
Fig. 9. LBB boundary lines for type 304 stainless steel piping with infinite compliance.

R. Kurihara, S. Ueda, and D. Sturm, "Estimation of the Ductile Unstable Fracture of Pipe with a Circumferential Surface Crack Subjected to Bending," *Nuclear Engineering and Design*, Vol. 106, pp. 265-273, 1988.

April 4, 2007, NRC Letter

Nominal Stress in Adjacent Piping

- This plots shows nominal stress in the attached piping assuming the same pressure, axial force, and effective moment M_{eff} as reported for the nozzles
- The stress is shown relative to the Code yield strength based on preliminary piping material assumptions
- These results show yield level stresses in
  - some safety/relief and spray nozzle cases
  - all surge nozzle cases
- The results may be relevant regarding the role of secondary stress in the crack stability calculations



Status of NRC Confirmatory Research

- To be presented by NRC

Proposed Case Matrix
Items

- *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

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_i/t	Weld Sep. (in.)	Butter Weld Repairs	ID Weld Repairs	OD Weld Repairs	Design #	Piping NPS	Liner?	DM Weld t (in.)	DM Weld R_i/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_i/t	Weld Sep. (in.)	Butter Weld Repairs	ID Weld Repairs	OD Weld Repairs	Design #	Piping NPS	Liner?	DM Weld t (in.)	DM Weld R_i/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

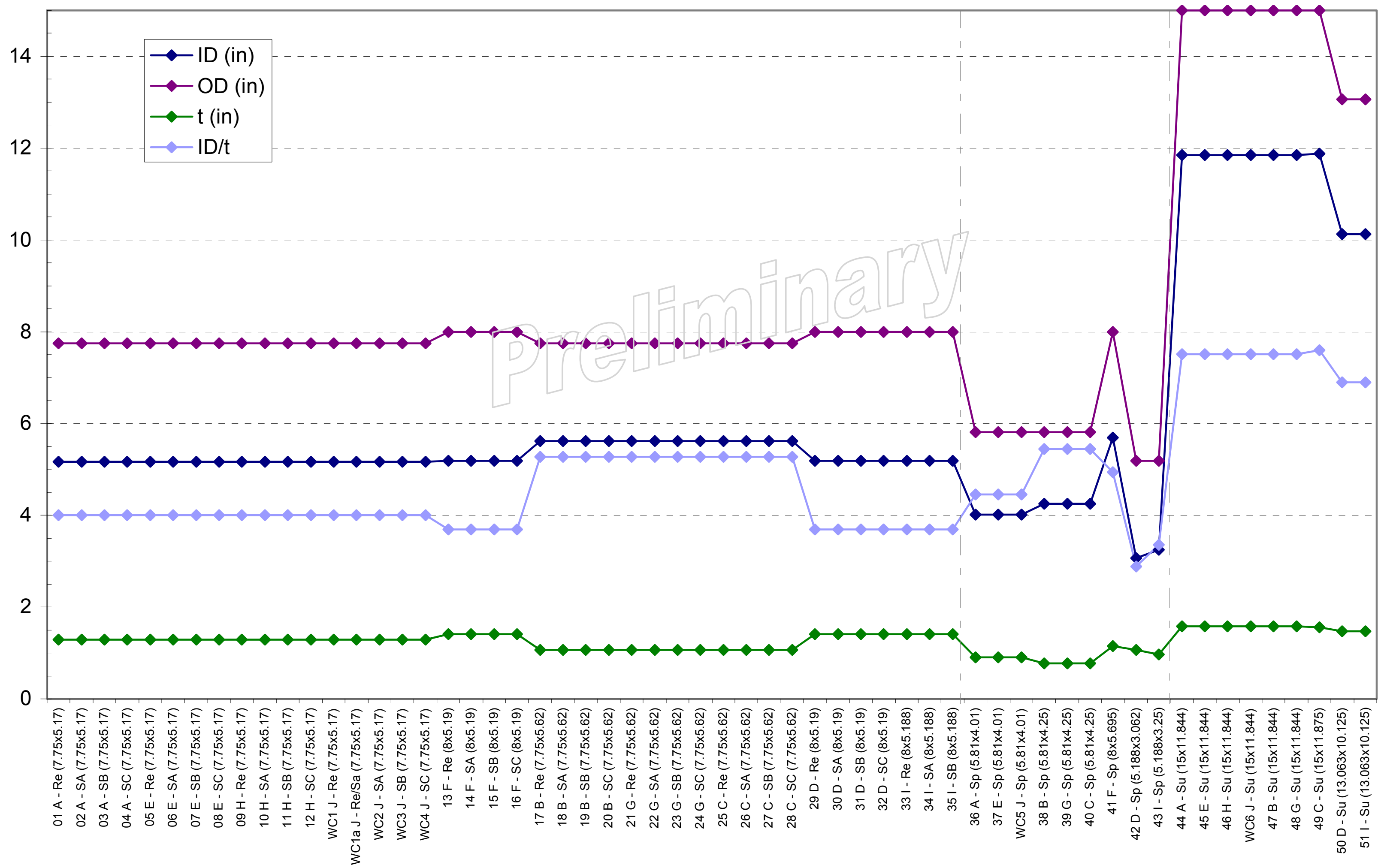
PRELIMINARY Summary Table (cont'd)

Plant Code	Spray (all have thermal sleeve)									Surge (all have thermal sleeve)								
	Design #	Piping NPS	Liner?	DM Weld t (in.)	DM Weld R_i/t	Weld Sep. (in.)	Butter Weld Repairs	ID Weld Repairs	OD Weld Repairs	Design #	Piping NPS	Liner?	DM Weld t (in.)	DM Weld R_i/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 overlayed								
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



Nozzle Geometry for Subject Plants

As-Built Dimensional Information

- Available as-built dimensions are being collected for the subject welds
- This information is being used to investigate as-built versus design dimensions:
  - DM weld OD (average between toe on nozzle and toe on safe end)
  - DM weld thickness
  - Separation distance between DM and SS welds
- Sensitivity cases for the crack growth and crack stability calculations are planned to check sensitivity to as-built dimensions

As-Built Dimensional Information

Review of Plant H As-Built Dimensions

- Following as-built dimensions are preliminary
- Safety/Relief
  - LAS nozzle end thickness of 1.16″ - 1.37″ vs. design of 1.42″ (including cladding)
  - Butter thickness of 0.80″ vs. design of 0.81″
- Spray
  - LAS nozzle end thickness of 0.87″ - 0.92″ vs. design of 1.00″ (including liner) and 0.88″ (without liner)
  - Safe end OD at DM weld of ~5.65″ vs. design of 5.62″
- Surge
  - LAS nozzle end thickness of 1.40″ - 1.60″ vs. design of 1.51″ (including cladding)
  - Butter thickness of 0.30″ vs. design of 0.81″
- In general, as-built thickness of butter buildup on LAS nozzle end can vary significantly

As-Built Dimensional Information

Review of Plant C As-Built Dimensions

- Following as-built dimensions are preliminary
  - There is uncertainty in the weld separation figures because only axial length of various materials on OD is provided
- Relief
  - Separation distance of ~2.18″ vs. design of 2.32″
  - DM weld circumference of 24.5″ vs. design of 24.3″ (based on average OD of 7.75″)
  - DM weld thickness of 1.14″ vs. design of 1.07″ (without liner)
- Safety A
  - Separation distance of ~2.2″ vs. design of 2.32″
- Safety B
  - Separation distance of ~1.85″ vs. design of 2.32″
  - DM weld thickness of 1.08″ vs. design of 1.07″ (without liner)
- Safety C
  - Separation distance of ~2.3″ vs. design of 2.32″
  - DM weld thickness of 1.14″ vs. design of 1.07″ (without liner)

As-Built Dimensional Information

Review of Plant C As-Built Dimensions (cont'd)

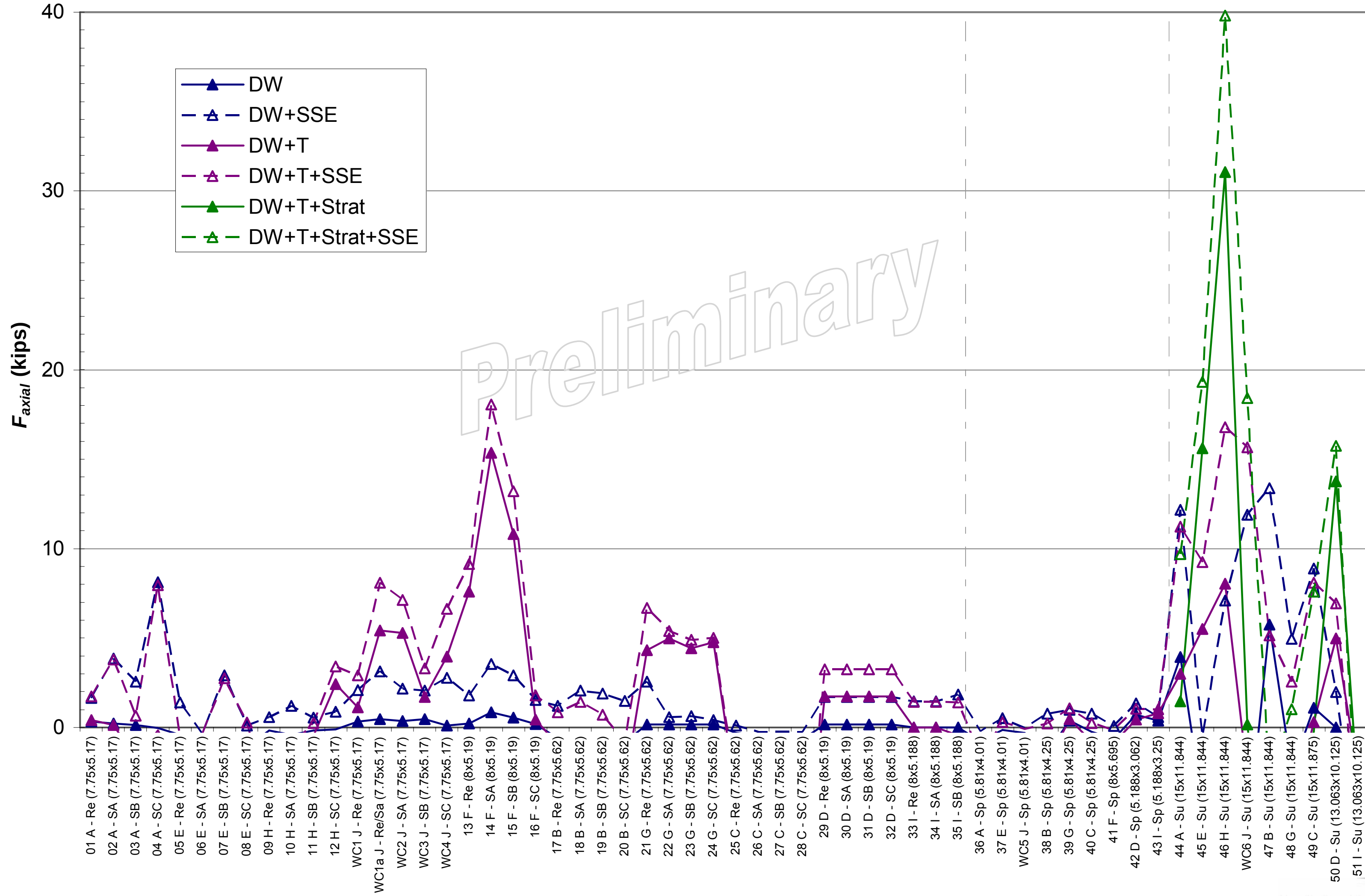
- Spray
  - Separation distance of ~3.25″ vs. design of 2.2″
- Surge
  - Separation distance of ~3.73″ vs. design of 3.46″
  - Average DM weld thickness of 1.501″ vs. design of 1.563″
  - DM weld circumference of 46.875″ vs. design of 47.12″ (based on OD of 15.00″)

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

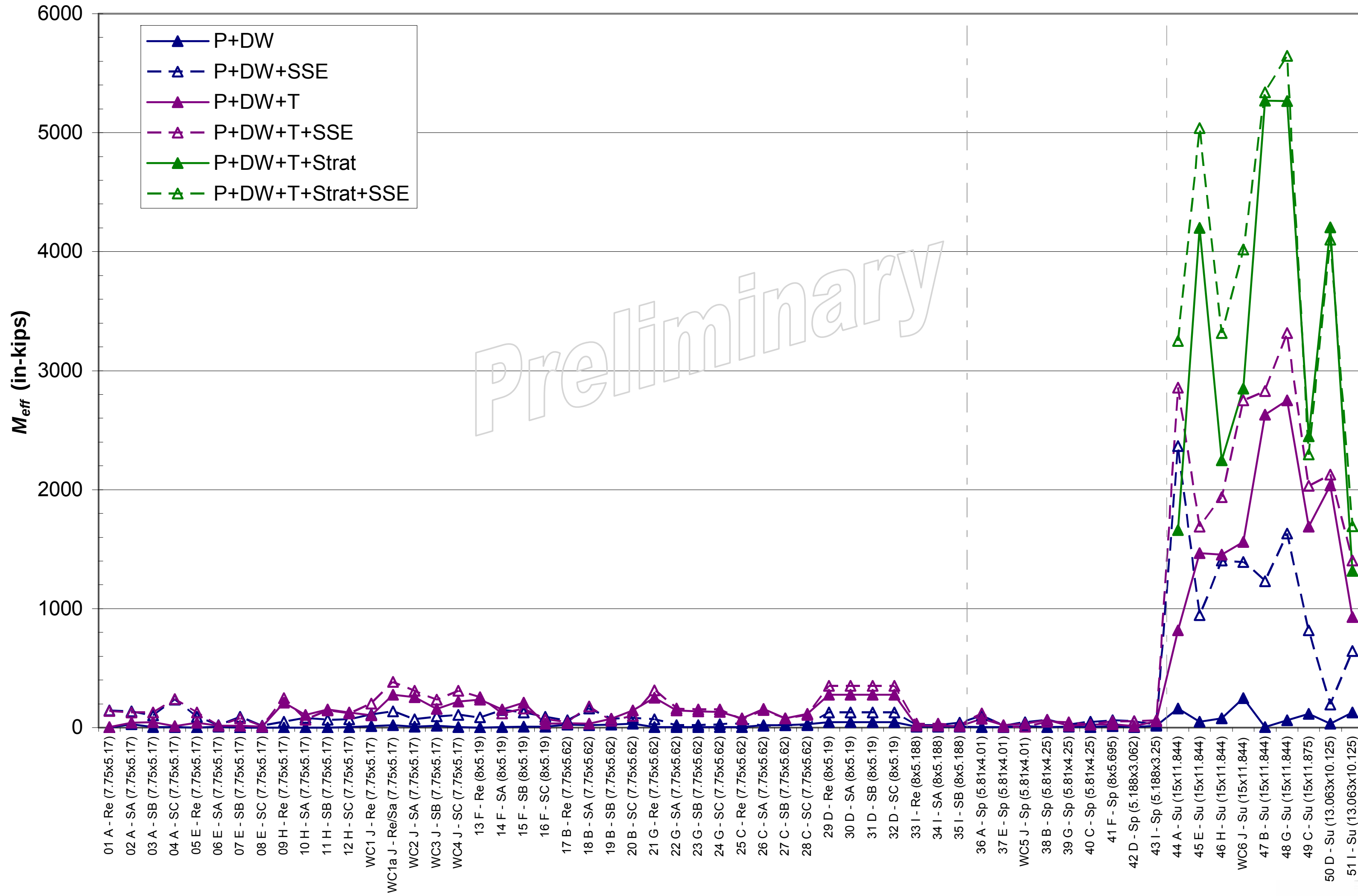
Plant-Specific Piping Loads

Nominal Axial Piping Loads *(Not Including Endcap Pressure Load)*



Plant-Specific Piping Loads

Nominal Effective Bending Moment Load (Full Scale)



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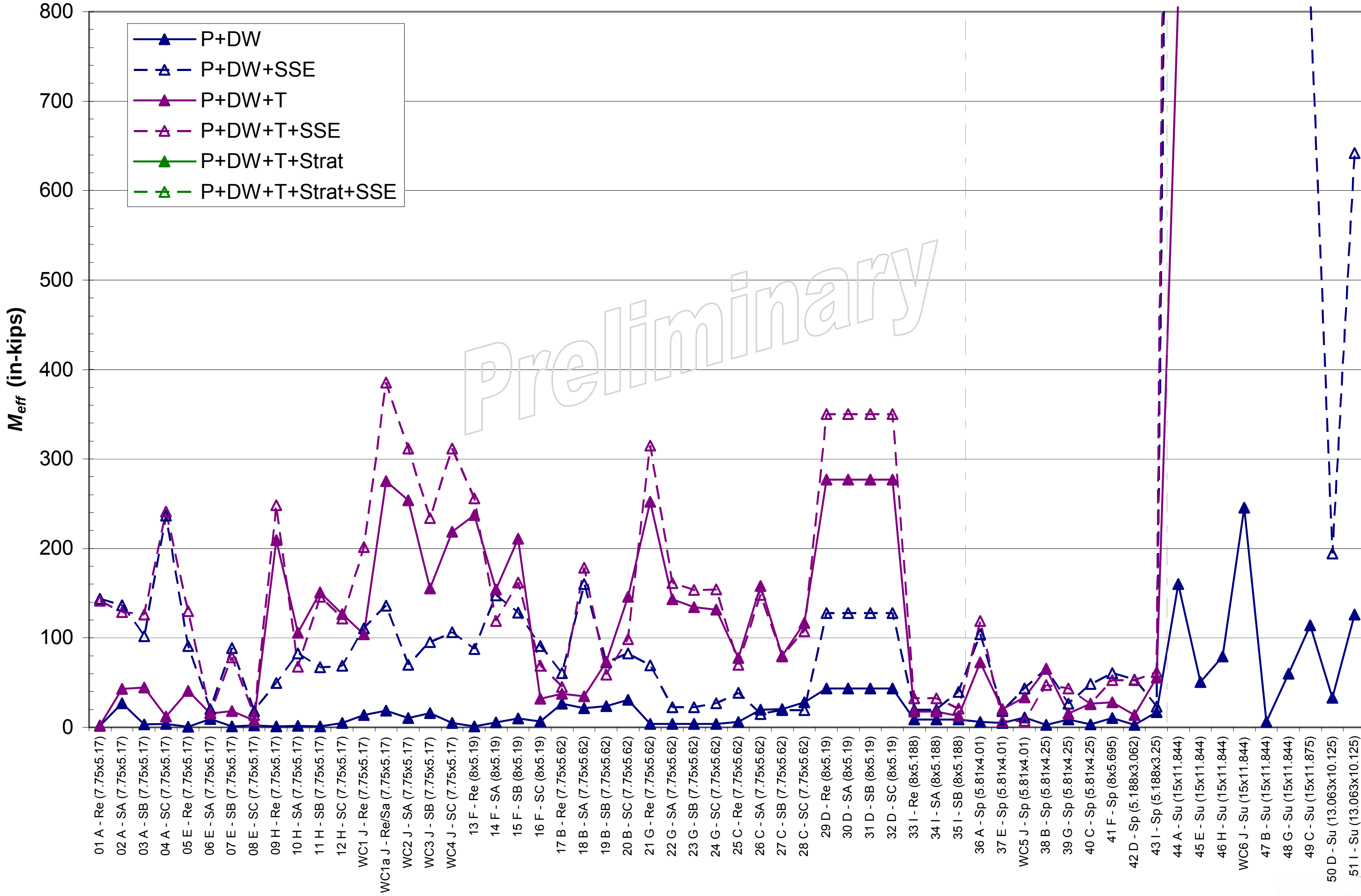
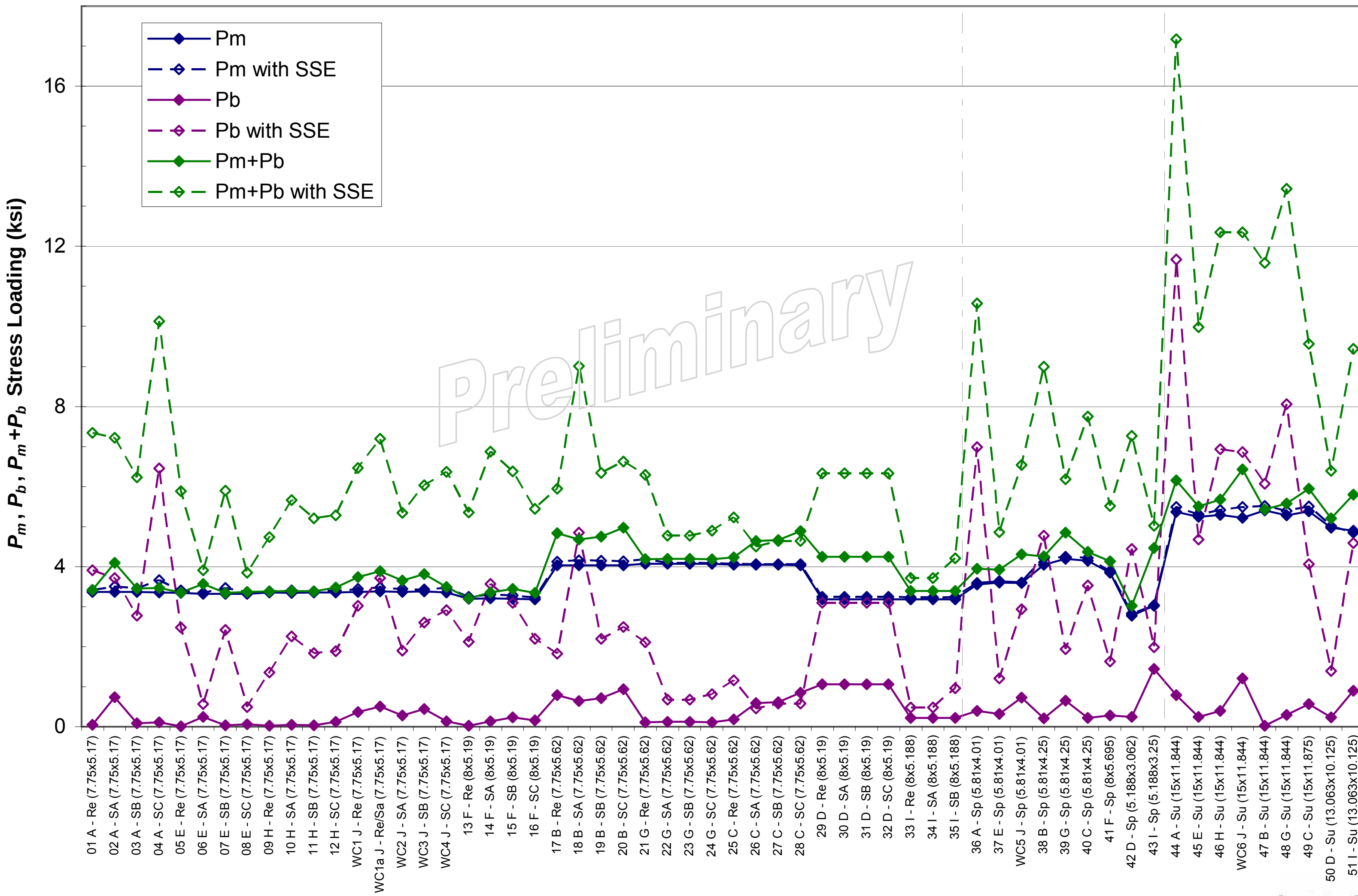
Plant-Specific Piping Loads

Nominal Effective Bending Moment Load (Partial Scale)



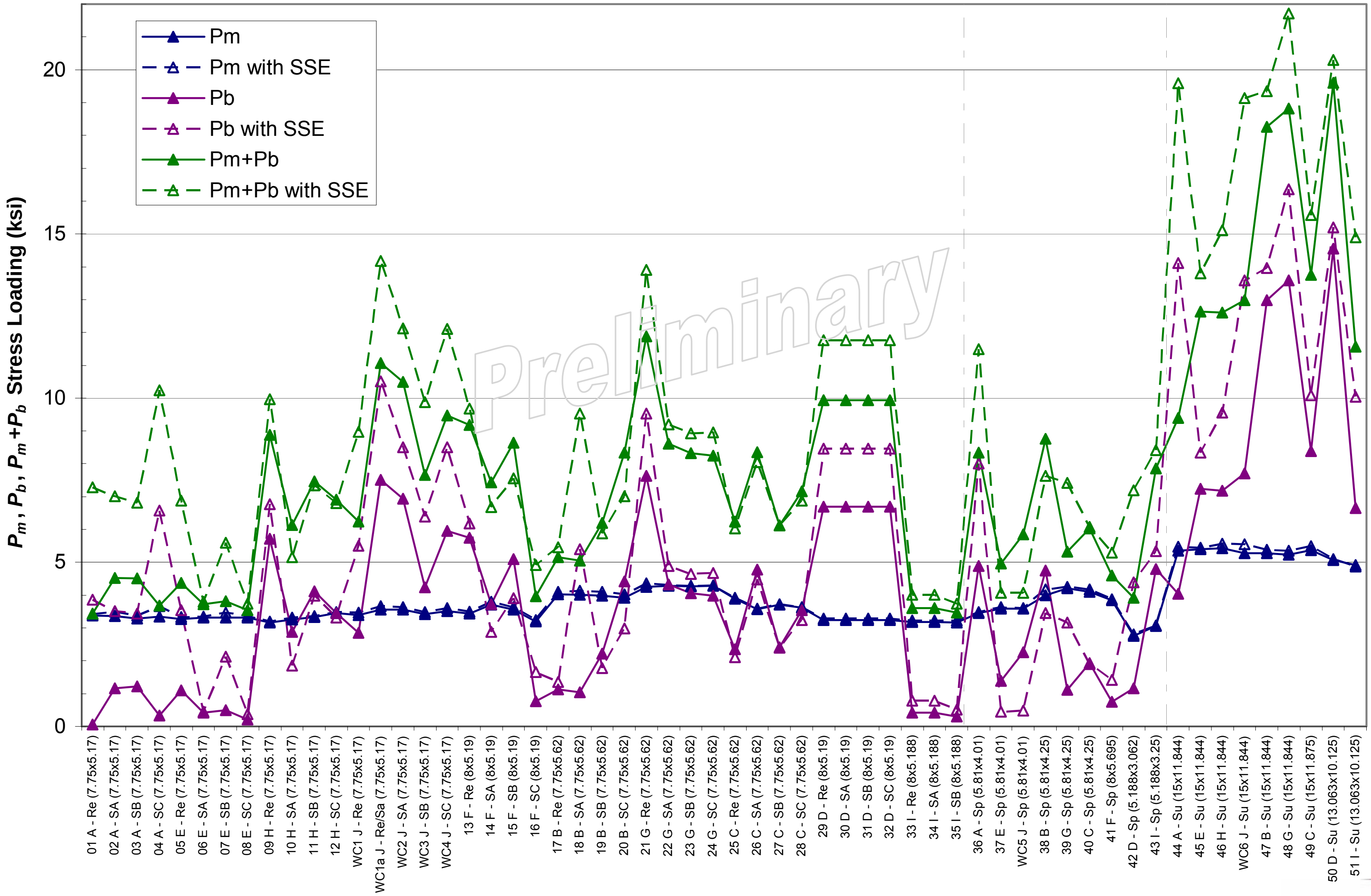
Plant-Specific Piping Loads

ASME Code Nominal Stress Loading for Pressure and Dead Weight Loading



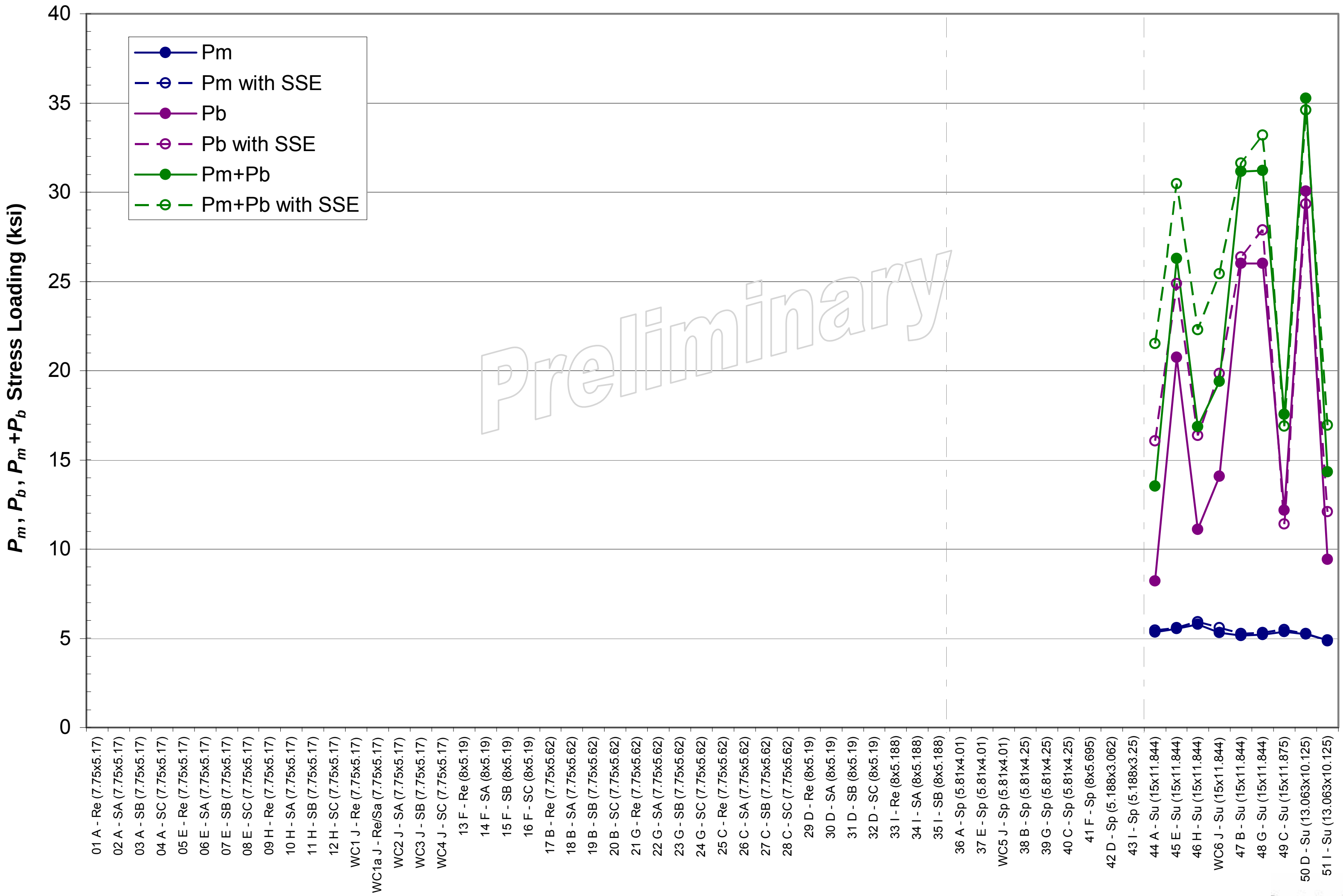
Plant-Specific Piping Loads

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



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Plant-Specific Piping Loads

Treatment of Loads in Crack Growth Modeling

- 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
  - Normal pipe thermal expansion: Axial force and bending moment applied to end of model (no credit taken for relaxation of load with crack opening)
  - Normal thermal stratification pipe bending moment (surge nozzle only): Added to normal thermal loads
  - Thermal stratification pipe bending moment for plant transients (surge nozzle only): Not relevant for crack growth
  - Welding residual stress: Multiple cases assumed as described separately below
  - Local thermal stress due to differential thermal expansion (Q-stress): Considered as a sensitivity case in cracked WRS model
  - Seismic loads: Not relevant for crack growth

Plant-Specific Piping Loads

Treatment of Loads in Crack Growth Modeling (cont'd)

- For global moment loads, the following equation (NUREG/CR-6299) is being used 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

Proposed Case Matrix
Welding Residual Stress

- Summary of May 1 Meeting
- Fabrication Steps affecting WRS
  - Last Pass Fill-In Weld (Surge)
  - Fillet Welds (Safety/Relief)
  - Buildup on Safe End ID
- Repairs
  - Deep ID Repairs
  - ID Repairs on Spray Nozzle?

Welding Residual Stress

Agenda of May 1 Meeting at DEI Offices

- Nozzle and weld geometry cases for subject welds
- Collected weld repair information for subject welds
- Application of WRS FEA models
  - Previous FEA results by DEI (MRP-106)
  - FEA work by Battelle and EMC2 (presentation by Dave Rudland, EMC2)
  - Discussion of approach to new FEA for selected subject weld cases
- WRS data for piping butt welds in open literature
- Candidate WRS profiles
  - Axisymmetric profiles
  - Non-axisymmetric profiles
- Validation of WRS inputs
- Meeting wrap-up

Proposed Case Matrix

Tentative New FEA WRS Cases Planned at May 1 Meeting

- Effect of SS weld on stress in DM weld
  - One axisymmetric case to be selected based on design and available as-built weld separation data
  - Influence is expected to depend on $\Delta x/t$ and R_i/t, where Δx is the weld separation distance
- Surge nozzle cases
  - No repairs with fill-in weld
  - 0.5″ deep ID repair followed by fill-in weld
  - CE nozzle case with no fill-in weld
- Spray nozzle cases
  - Consider deferring until Plant C and F weld repair records are searched
- Safety/relief nozzle cases
  - Model effect of 1/8″ weld buildup on safe end ID (geometry based on WC)
  - No repairs with liner fillet weld
  - ¾″ deep ID repair followed by liner fillet weld
    - Consider modeling short, deep repairs using 3D model

Development of WRS Cases
Approach

- Because of the uncertainty in the true residual stress field in each of the 51 subject welds, a matrix of sensitivity cases will be considered covering a wide range of WRS patterns
- Range of welding residual stress profiles
  - Axisymmetric (self balance at every circumferential position)
  - Non-axisymmetric (self balance over entire cross section)
  - Weld fabrication and repair data compiled as input to selection of WRS profiles for analysis
- As previously planned, the following sources will be applied to develop the WRS cases considered:
  - Weld fabrication and repair data from construction for the 51 subject welds
  - 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 51 subject welds considering the weld fabrication information
  - WRS data in the open literature
    - FEA simulations
    - Stress measurements on mockups and removed components

Development of WRS Cases
Approach (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

Welding Residual Stress Inputs

Weld Fabrication and Repair Data Compiled for Wolf Creek

- Available data on initial weld fabrication and repair has also been compiled for the subject welds
  - See next two slides

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 outs 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 outs 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).*

Nozzle Geometry and Repair History

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.

Nozzle Geometry and Repair History

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.

Welding Residual Stress

Conclusions of Previous DEI Work for EPRI (MRP-106, etc.)

- 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°

Piping Butt Weld WRS – Literature Review

Preliminary Conclusions

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

Validation of WRS Inputs
Approach

- 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
  - International round robin, if needed details can be made available

Validation of WRS Inputs

Approach (cont'd)

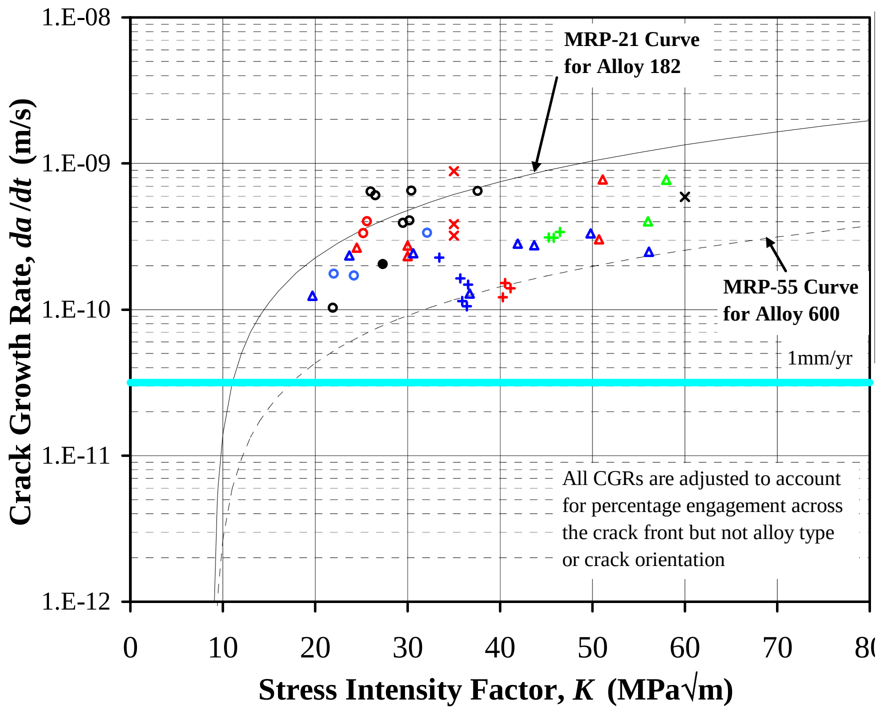
- In past comparisons, the results of the DEI WRS model have shown reasonable agreement versus measured WRS:
  - Measured CRDM nozzle mockup stress
  - Measured BWR shroud support weld stress
  - Measured CRDM nozzle ovality

Proposed Case Matrix
Crack Growth Rate Equation

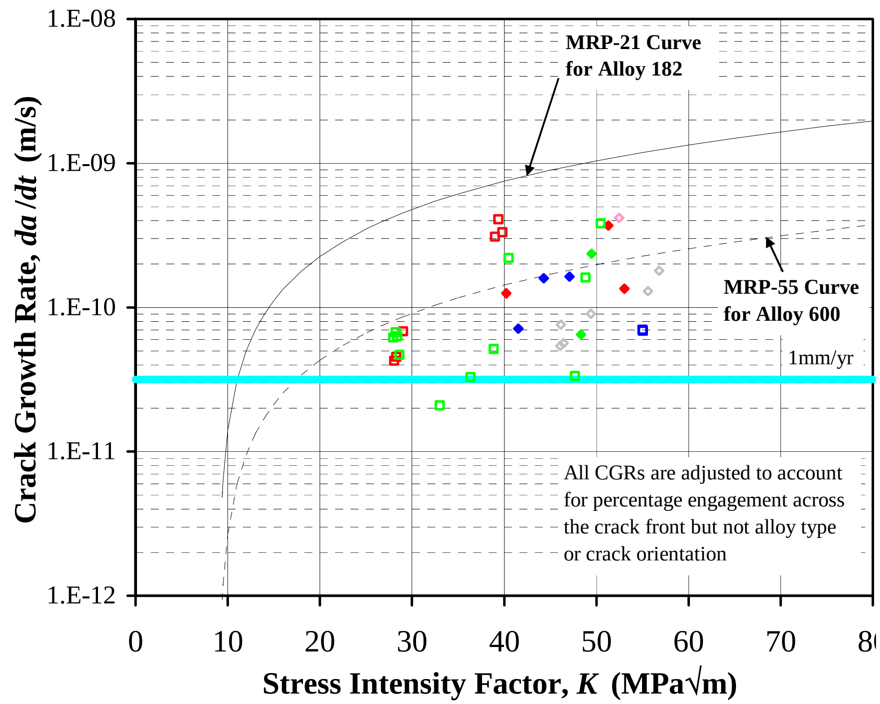
- Sensitivity cases will examine the effect of main uncertainties in the MRP-115 CGR equation:
  - Uncertainty in the SIF power-law exponent (nominal 1.6)
  - Uncertainty in power-law constant (only time scaling factor that would affect time between leakage and rupture but not whether leakage prior to rupture)
- The following factors are not expected to be explicitly evaluated using the FEACrack software
  - 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)
- No credit being taken for a SIF threshold

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)

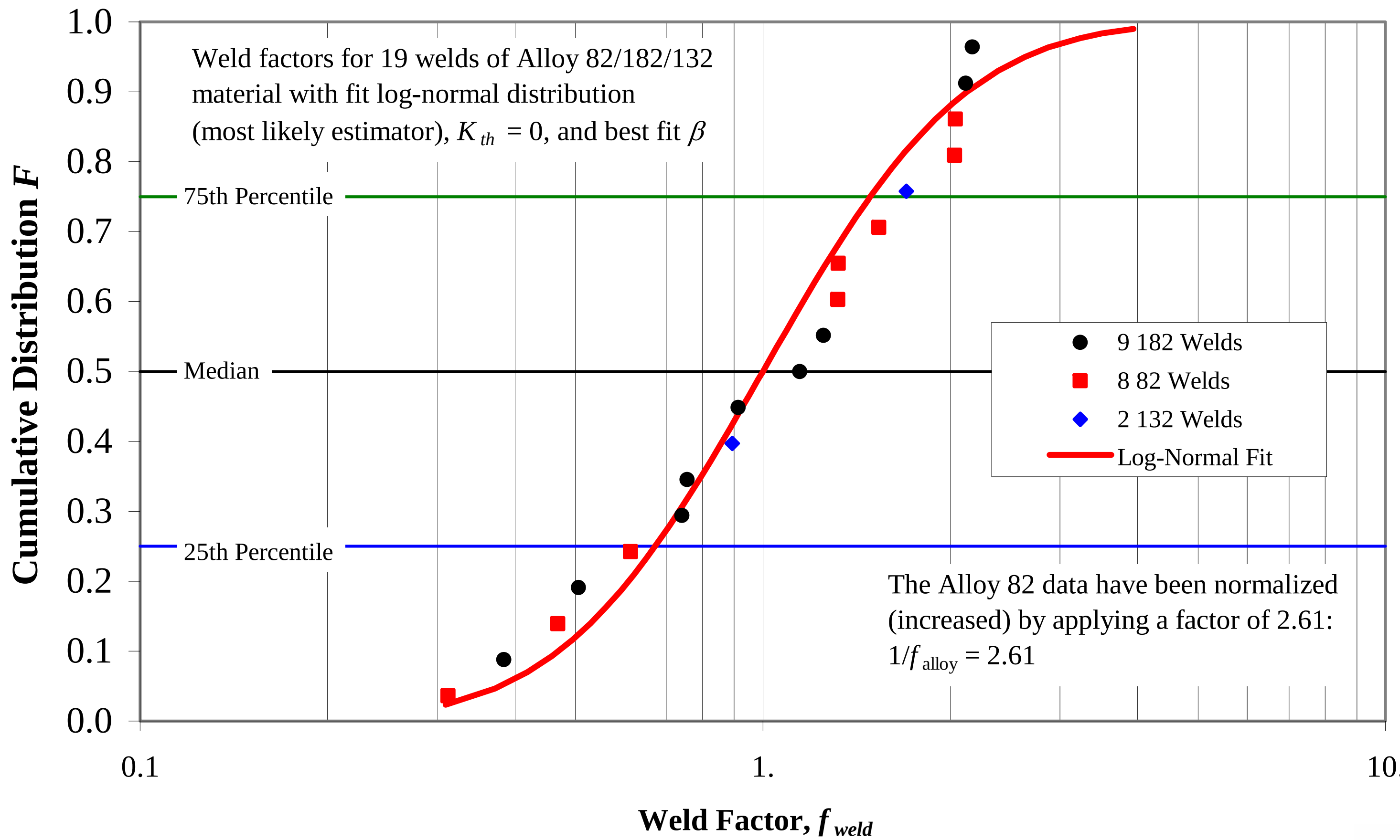


Average CGR data for Alloy 82 after screening (34 points)

MRP-115 Crack Growth Rate Equation

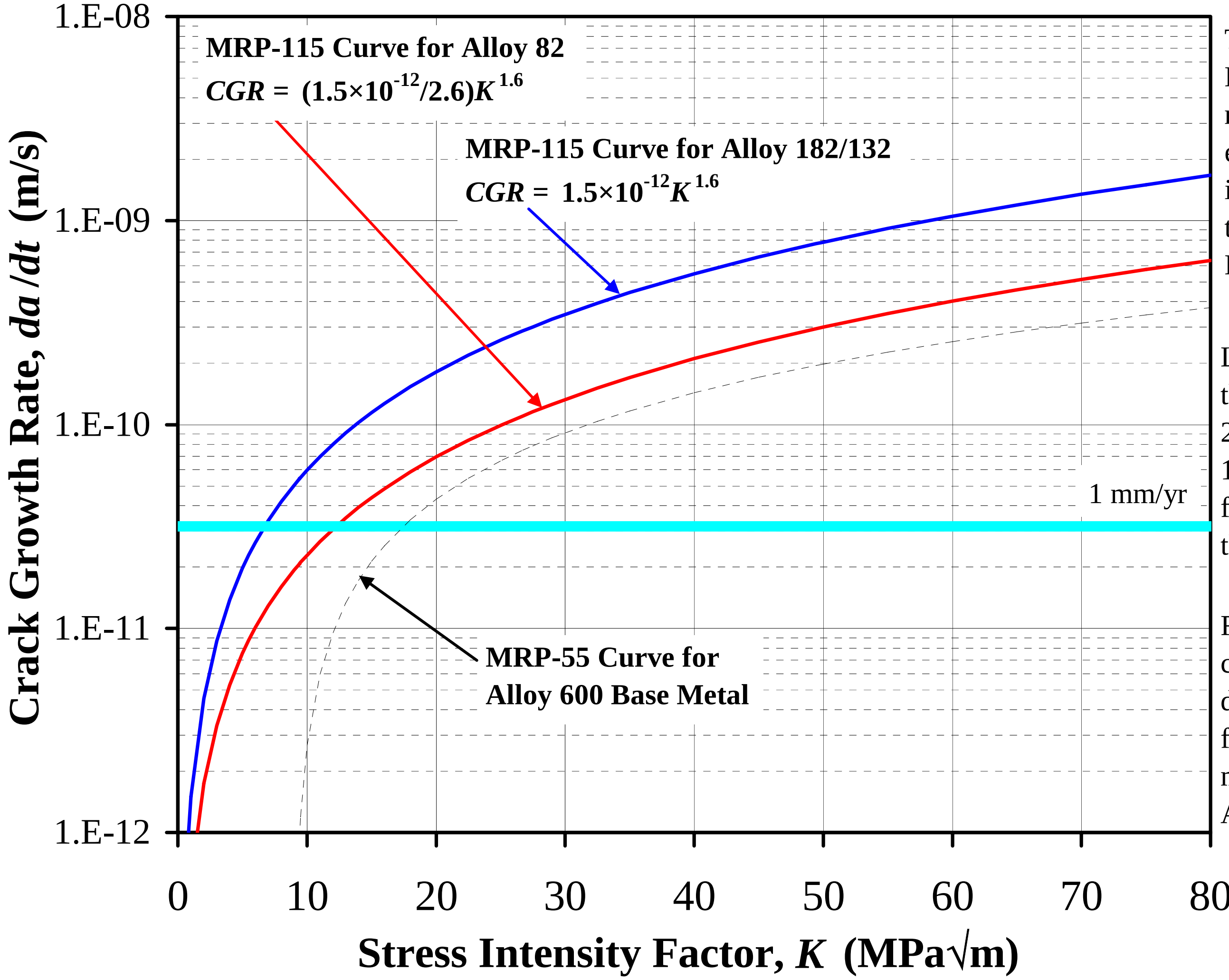
Distribution of Screened Data by "Weld Factor"

- The variability in "weld factor" from the statistical evaluations of laboratory CGR data in MRP-115 will be used to investigate the effect of uncertainty in the power-law constant



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.

Proposed Case Matrix

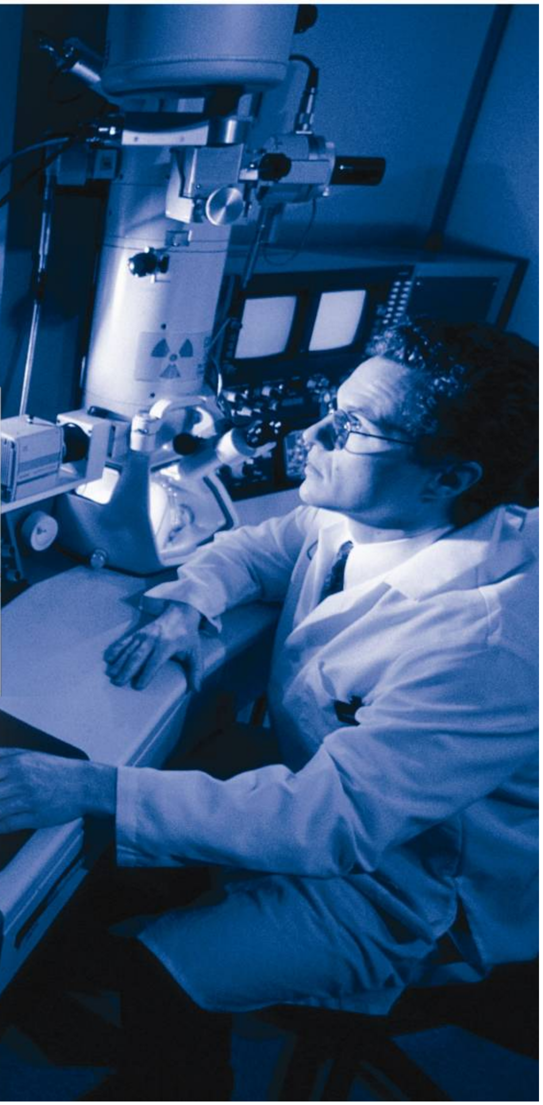
Effect of Multiple Cracks

- 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
- Sensitivity cases will investigate the effect of multiple crack initiation
- Several potential approaches are being considered:
  - 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
- See Quest Reliability, LLC slides on this topic

QUEST RELIABILITY

Asset Longevity | Plant Performance

Crack Interaction



Greg Thorwald, Ph.D.

303-415-1475

Coplanar Cracks

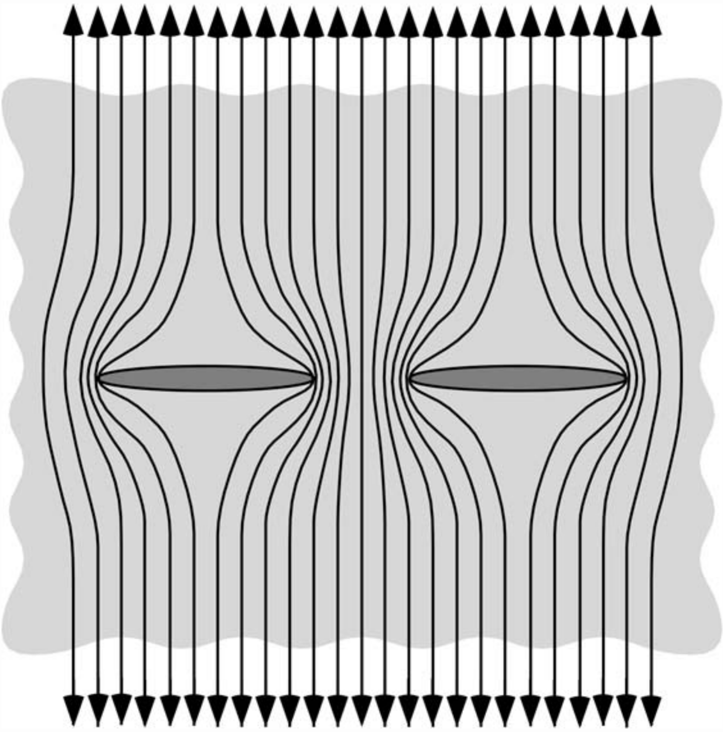


Fig 2.57 Two Coplanar cracks, interaction magnifies K_I at nearest crack tips

Crack Tip Interaction

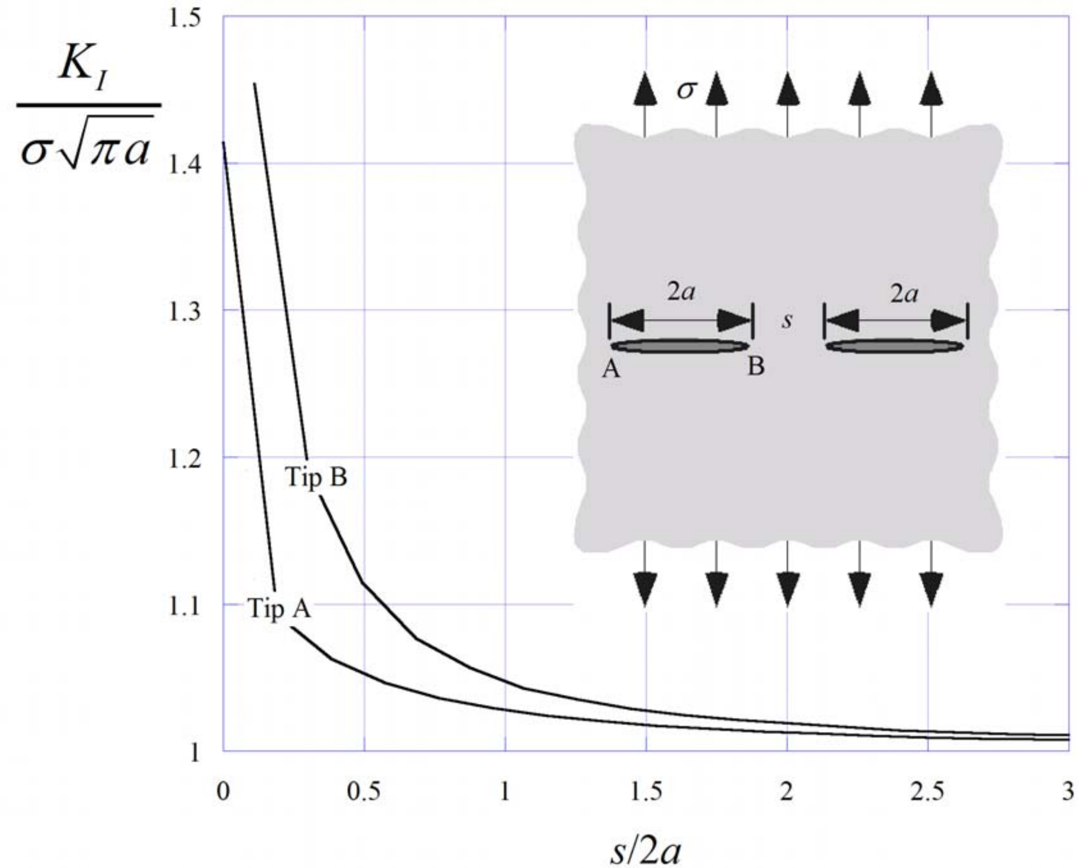


Fig. 2.58 Interaction of two identical coplanar through-wall cracks in an infinite plate; K_I magnified at crack tip B

Parallel Cracks

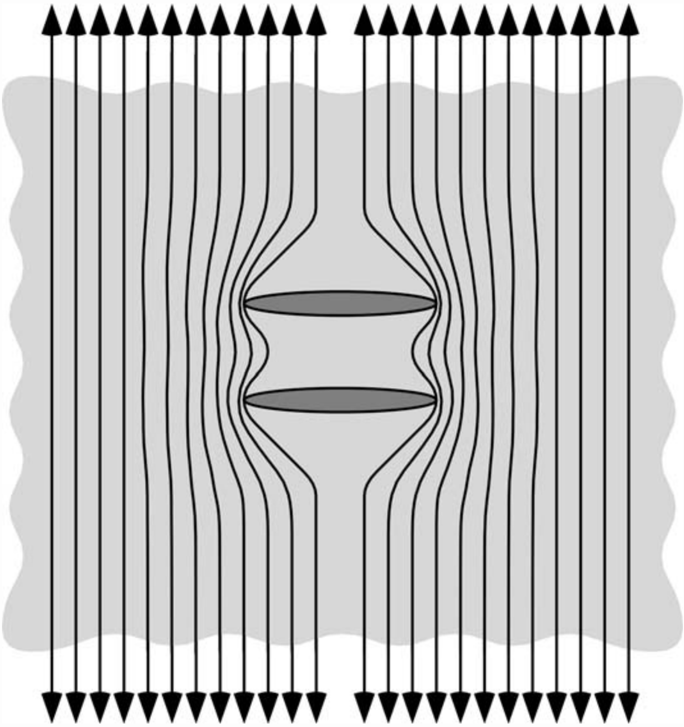


Fig. 2.59 Parallel cracks; shielding causes decrease in K_I

Parallel Crack Shielding

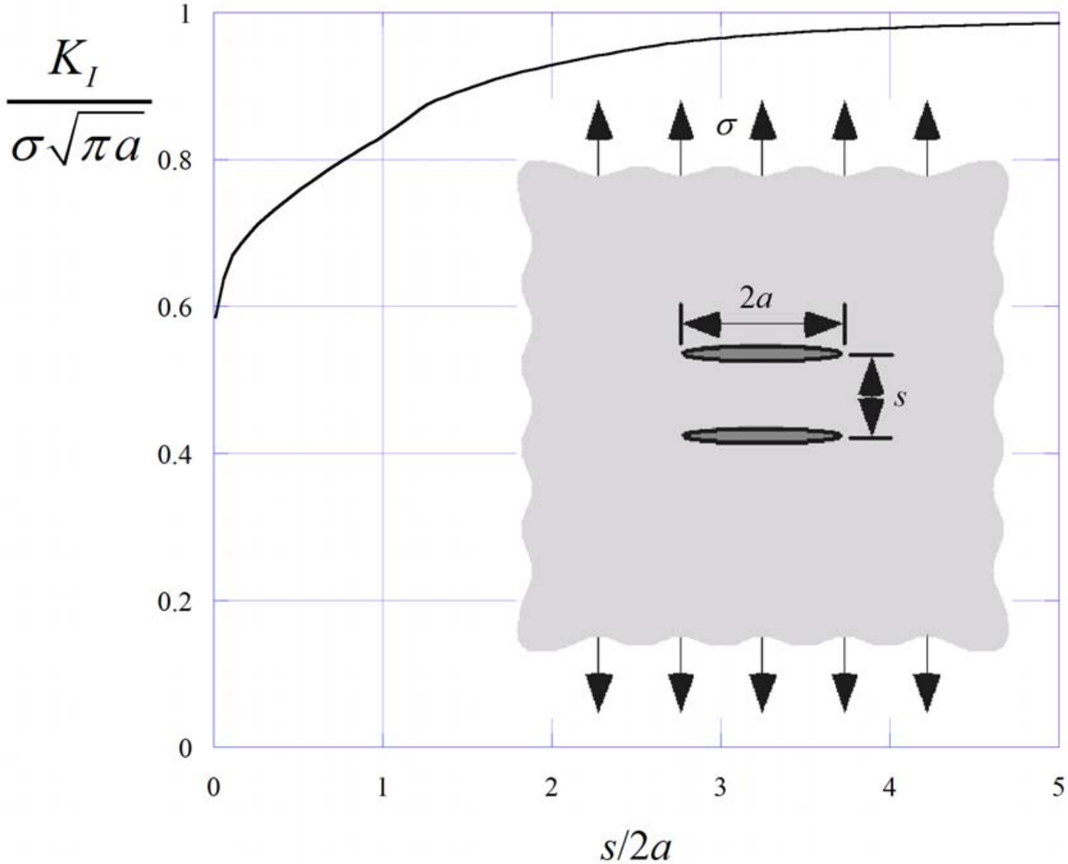


Fig. 2.60 Interaction between two identical parallel through-wall cracks in an infinite plate; crack tip shielding decreases K_I compared to a single crack

Crack Interaction Models

- Use a single crack and a symmetry plane near the crack tip to get K interaction
- Include multiple cracks in a model
- User-defined geometry method from FEACrack
  - Same or different crack shapes
  - Adjust distance between crack fronts

Proposed Case Matrix
Other Items: Initial Flaw Geometry

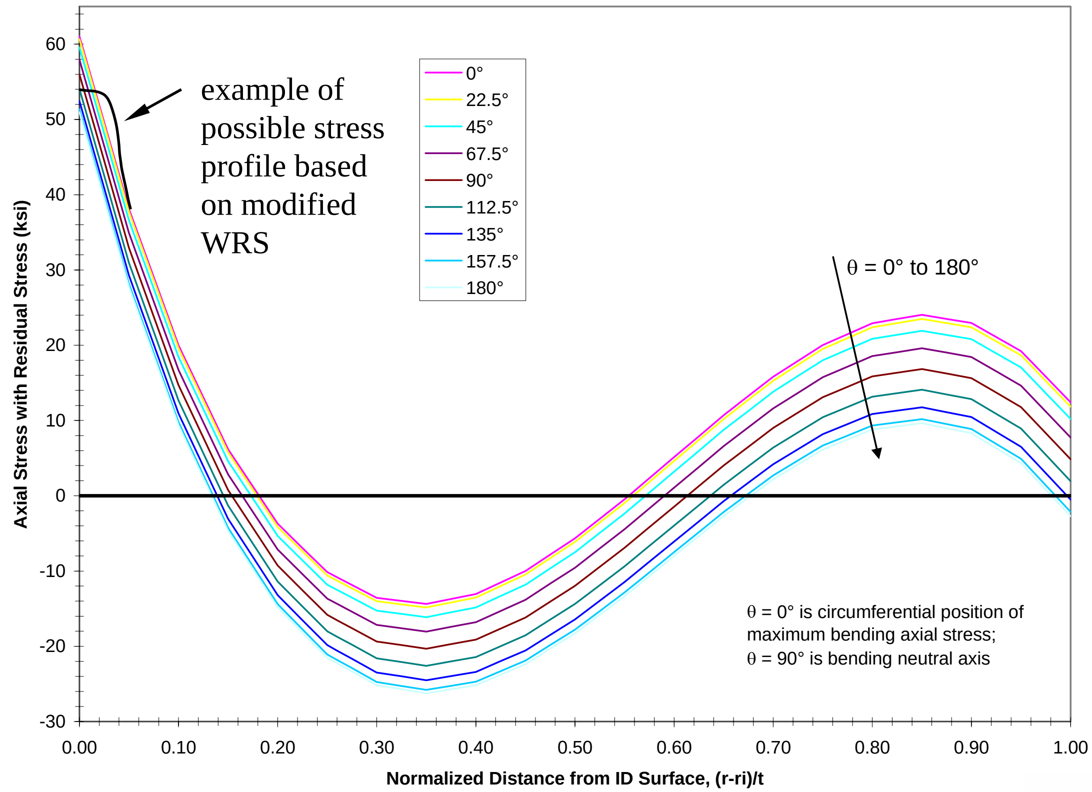
- Sensitivity cases will investigate the effect of initial flaw geometry
  - Initial depth
  - Initial aspect ratio (2c/a) or 360° uniform depth surface flaw
  - Initial shape factor (e.g., low shape factor to semi-ellipse to close to uniform depth)
- Cases for WC relief nozzle dimensions indicate that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

Proposed Case Matrix

Other Items: Effect of Elastic-Plastic Redistribution of Load

- Cases to investigate effect of elastic-plastic redistribution of load given high WRS at ID surface
  - The applied WRS profile may be modified to investigate this effect as implied in the following figure:

Plot for WC relief nozzle showing axial stress profile at various positions around circumference (dead weight, thermal pipe load, end cap pressure, and assumed WRS)



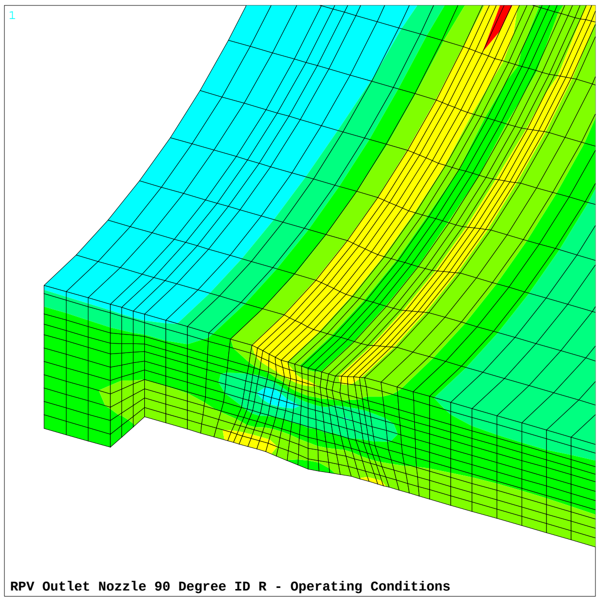
Proposed Case Matrix

Other Items: Crack Inserted into WRS FEA Model

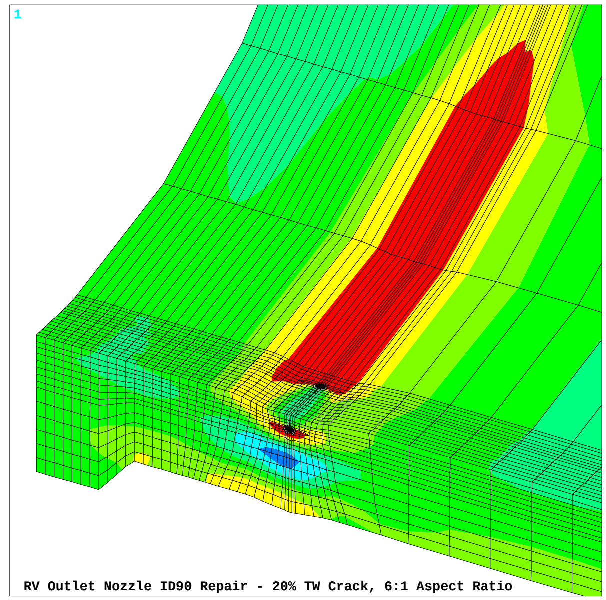
- It is planned for selected sensitivity cases, a crack will be inserted directly into the 3-dimensional DEI WRS FEA model
  - Considers detailed geometry effects
  - Considers detailed predicted WRS field, including modeling of weld repairs
  - Considers local thermal stress due to differential thermal expansion (Q-stress)

Proposed Case Matrix
Other Items: Crack Inserted into WRS FEA Model

- 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 this work will reduce the effort required to insert the crack mesh into the full welding residual stress model

Additional Topics – Industry and NRC

- Critical Crack Size Calculations
  - Industry
- Validation studies and WRS mockups
  - Industry
- Benchmarking NRC/Industry K Solutions for the Advanced FEA Calculations
  - Industry
  - NRC
- Leak-rate Calculations
  - Industry

Calculating Critical Crack Size
Approach

- Scoping calculations have been completed examining the dependence of critical crack size for idealized surface and through-wall crack geometries for the dimensions and load parameters for the group of 51 subject welds
  - Effect of load types included
  - Effect of assumed flow strength
  - Effect of thin-wall vs. thick-wall equations
  - Effect of surface vs. through-wall crack geometry
  - Effect of inclusion of Z-factor
- The flow strength in the net section collapse calculations will be based on the safe end material, given the potential for the crack to be located close to the safe end
- Crack stability for each calculated crack growth progression (surface crack and through-wall) is being checked using a spreadsheet implementation of the NSC solution published by Rahman and Wilkowski for an arbitrary crack profile, assuming thin-wall equilibrium

Calculating Critical Crack Size
Approach (cont'd)

- The Arbitrary Net Section Collapse (ANSC) software by Structural Integrity Associates is also being applied:
  - To verify the spreadsheet implementation of Rahman and Wilkowski (exact agreement has been obtained)
  - To investigate cases in which the moment direction is not assumed to be lined up with the symmetry (i.e., center) point on the crack
- Consider secondary stresses as appropriate
  - See separate presentation by Pete Riccardella of SI
- Apply Z-factor to reduce supportable moment to consider effect of EPFM failure mechanism for small calculated values of the nondimensional plastic zone parameter
  - See separate presentation by Pete Riccardella of SI
- As described above, the crack growth progression is also checked for the potential effect of local ligament collapse
  - For complex crack profile at point leakage becomes detectable
  - For complete growth progression to examine potential effect on the progression

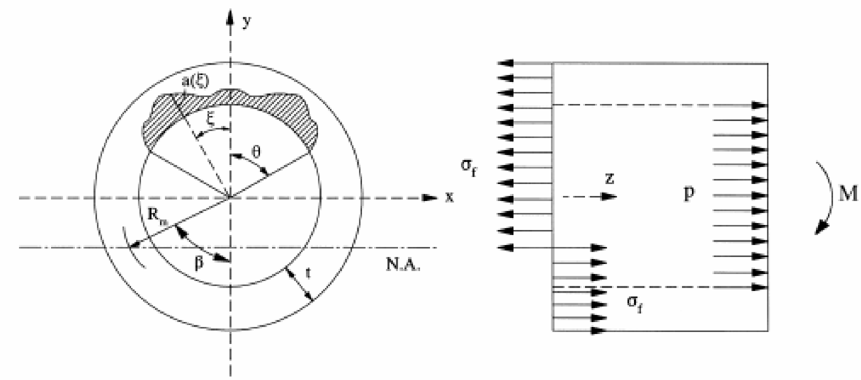
Calculating Critical Crack Size

Defining Pipe Loads for Critical Crack Size

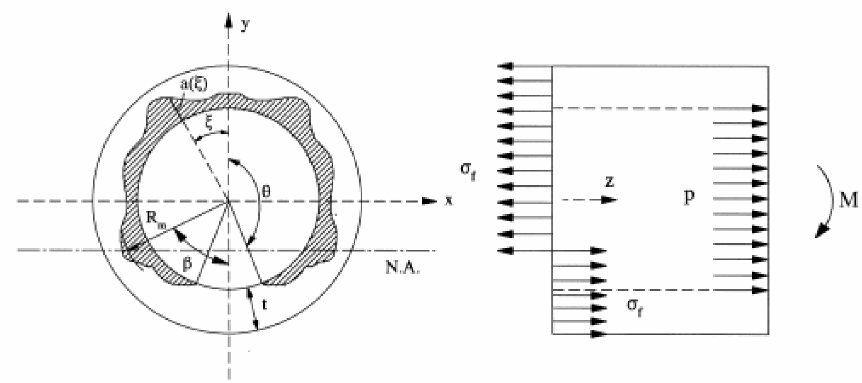
- Each category of loading is being treated as follows in the critical crack size calculation that defines the growth end point:
  - Deadweight: Same as for growth
  - Internal pressure: Same as for growth
  - Normal pipe thermal expansion: Treatment of secondary stresses discussed in presentation slides by Pete Riccardella of SI
  - Normal thermal stratification pipe bending moment (surge nozzle only): Treatment of secondary stresses discussed in presentation slides by Pete Riccardella of SI
  - Thermal stratification pipe bending moment for plant transients (surge nozzle only): Treatment of secondary stresses discussed in presentation slides by Pete Riccardella of SI
  - Welding residual stress: Not included in limit load or EPFM mechanisms
  - Local thermal stress due to differential thermal expansion (Q-stress): Not included as this is a local secondary stress component
  - Seismic loads: SSE load considered for faulted cases

Calculating Critical Crack Size
Force and Moment Equilibrium for Arbitrary Crack

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



(a) entire crack in tension (θ≤π-β)



(b) part of crack in compression (θ>π-β)

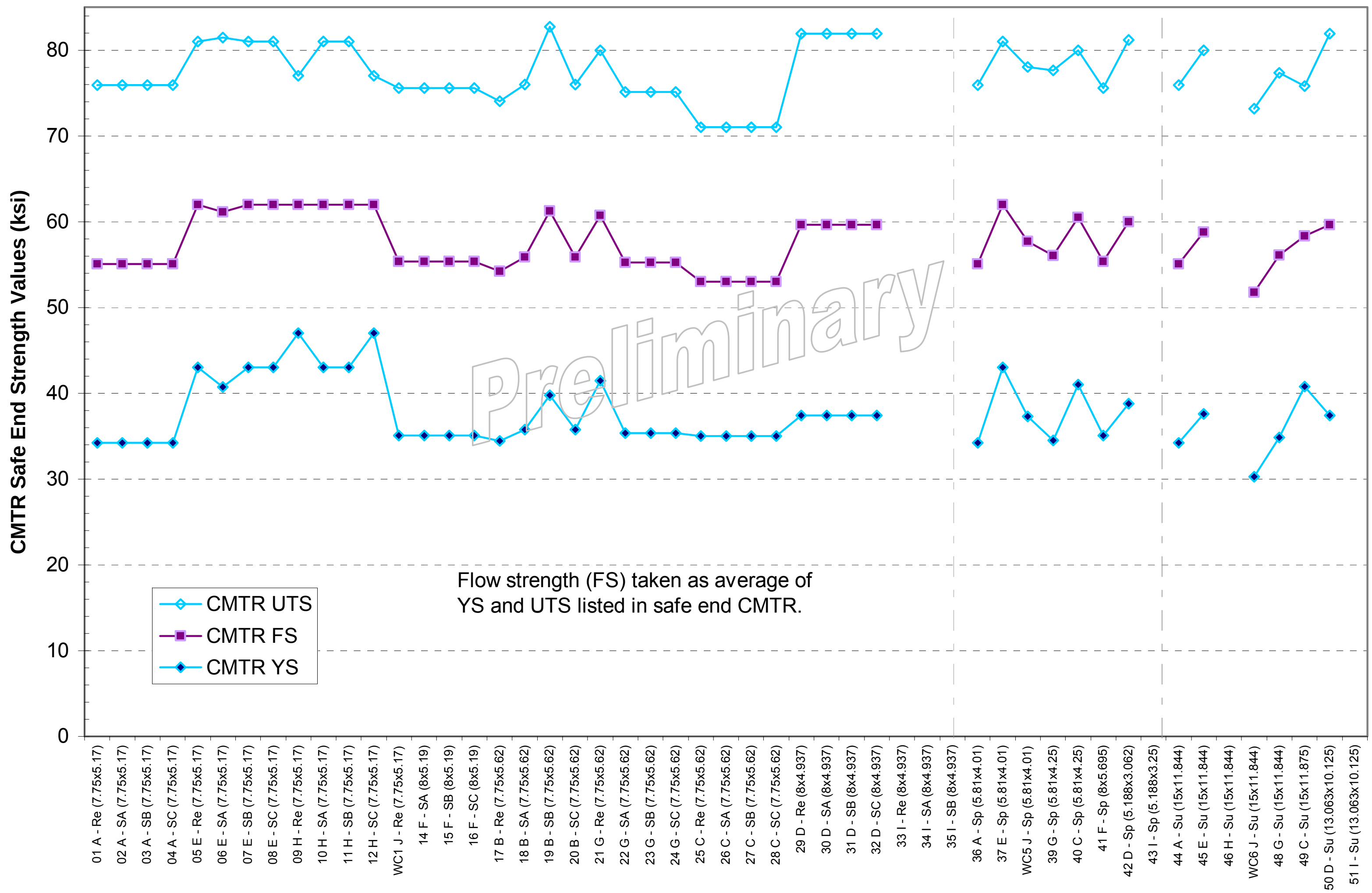
S. Rahman and G. Wilkowski, "Net-Section-Collapse Analysis of Circumferentially Cracked Cylinders—Part I: Arbitrary-Shaped Cracks and Generalized Equations," *Engineering Fracture Mechanics*, Vol. 61, pp. 191-211, 1998.

Calculating Critical Crack Size
Safe End Flow Strength

- Because any hypothetical SCC could be located close to the safe end material, the safe end flow strength will be applied in the limit load crack stability calculations
- Design drawings and CMTR information for 9 subject plants indicate that the stainless steel safe ends are fabricated from the following materials:
  - SA182 Grade F316L in most cases
  - SA182 Grade F316 in the other cases
- The following two slides show application of CMTR data to determine likely range of flow strength at temperature for the subject safe ends
  - Flow strength taken as average of yield and ultimate strength
  - Assumed temperature dependence between room temperature and 650°F based on Code temperature dependences for these materials: $S_{650°F} = CMTR \times (Code_{650°F}/Code_{RT})$
- The results of this investigation support the use of the 45.6 ksi flow strength value assumed in the NRC calculations for the WC safe end

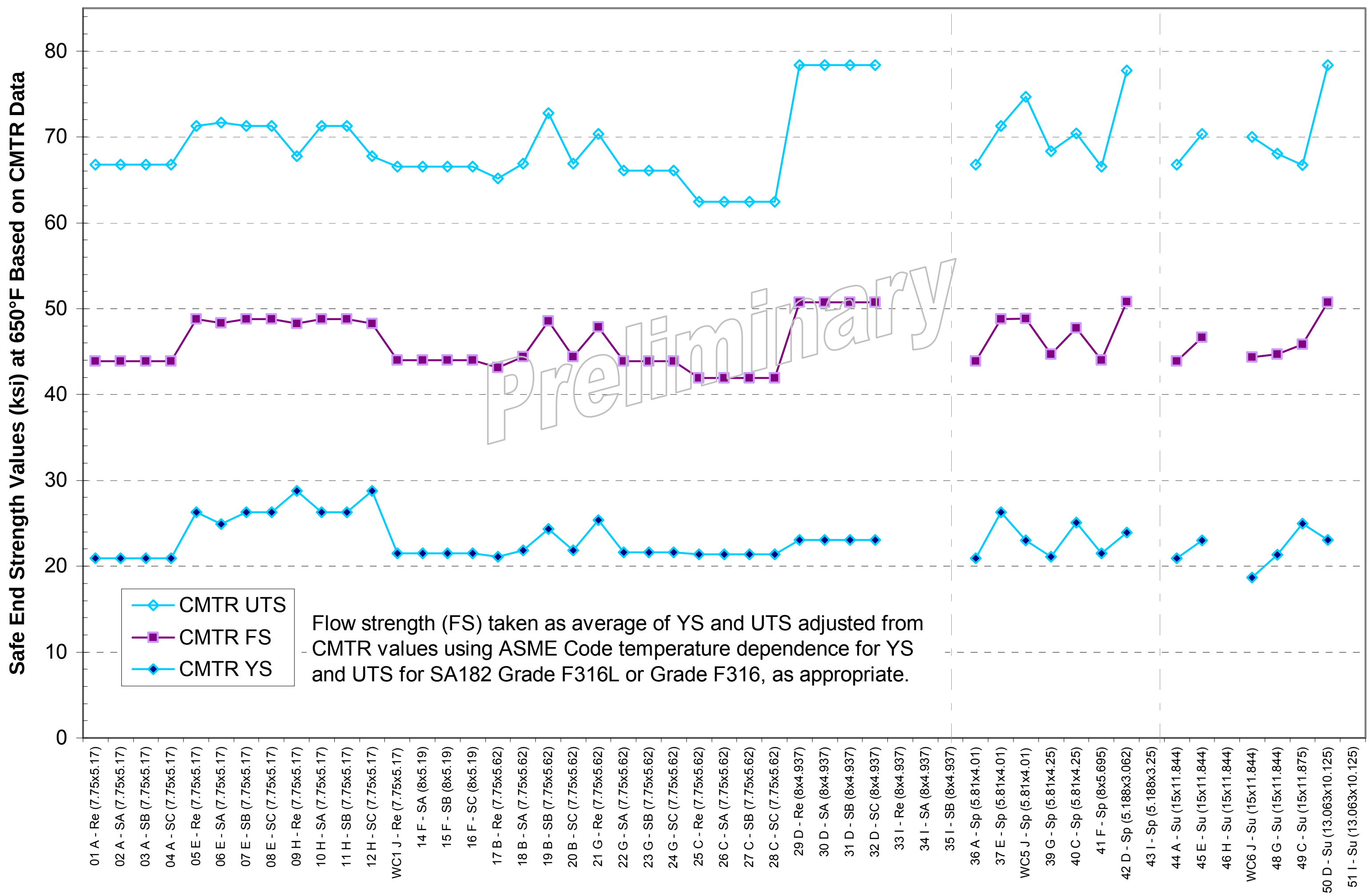
Calculating Critical Crack Size

CMTR Strength Values for Safe Ends



Calculating Critical Crack Size

Estimated Safe End Flow Strength at 650°F



Work Status
Validation Planning

- Validation planning is in progress, including consideration of application of the following:
  - MRP-107 laboratory study for Alloy 182 pressure capsules
  - Duane Arnold circumferential crack
  - Ringhals 3 reactor vessel outlet nozzle axial flaws left in service
  - Tsuruga 2 pressurizer safety and relief nozzle axial through-wall flaw associated with OD weld repairs
  - VC Summer reactor vessel outlet nozzle leaking flaw, primarily in axial direction
- For other PWR experience with possible PWSCC in Alloy 82/182 piping butt welds, destructive examinations have not been performed

Validation Planning

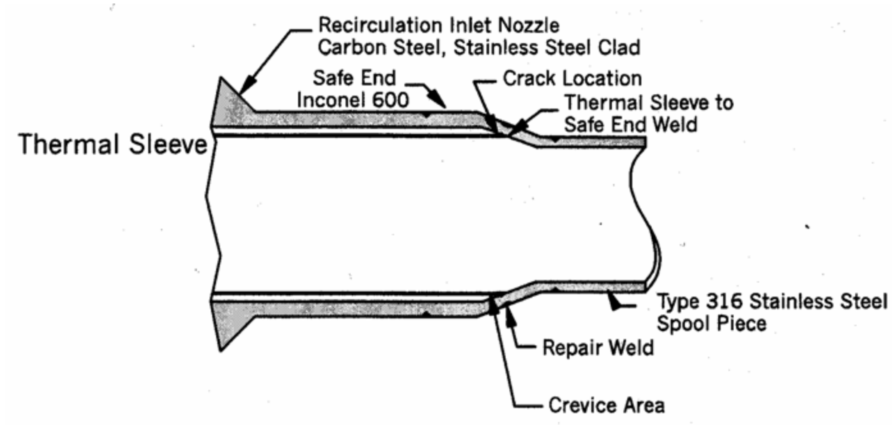
MRP-107 Lab Study of PWSCC in Alloy 182

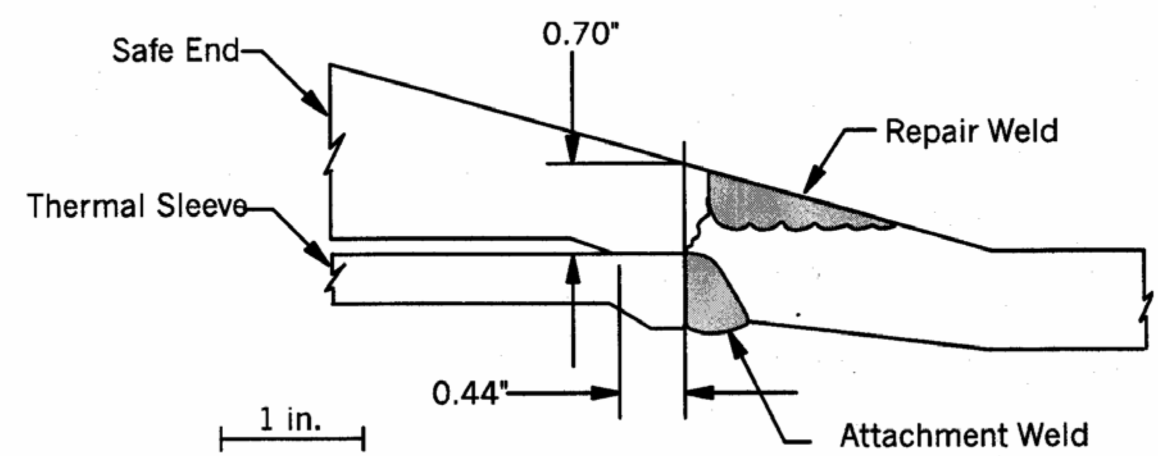
- The report summary for MRP-107 (EPRI 1009399, 2004) includes the following:
  - "Abstract: Detailed examinations of Alloy 182 capsule samples containing PWSCC established the relationship between crack initiation sites and the microstructure of the weld metal. These examinations also identified microstructural features that facilitate or arrest PWSCC propagation. Crack initiation only occurred at high angle, high energy, dendrite packet grain boundaries, and growth apparently arrested at low energy boundaries due to low angular misorientation or coincidence of lattice sites. <u>The work also revealed important findings with regard to crack geometries, in particular what aspect ratios may develop during PWSCC of nickel-base (Ni-base) weld metals.</u>"
  - "The cracks exhibited an unusual aspect ratio in that they never showed a large lateral surface extent, even when they extended through the wall thickness. This is a very different feature compared to PWSCC in Ni-base alloys such as Alloy 600. The aspect ratio is thought to relate to indications of crack arrest observed at low energy grain boundaries in Alloy 182."

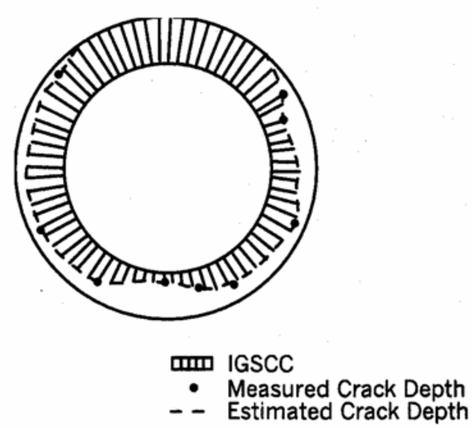
Validation Planning

Duane Arnold Circumferential Crack

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



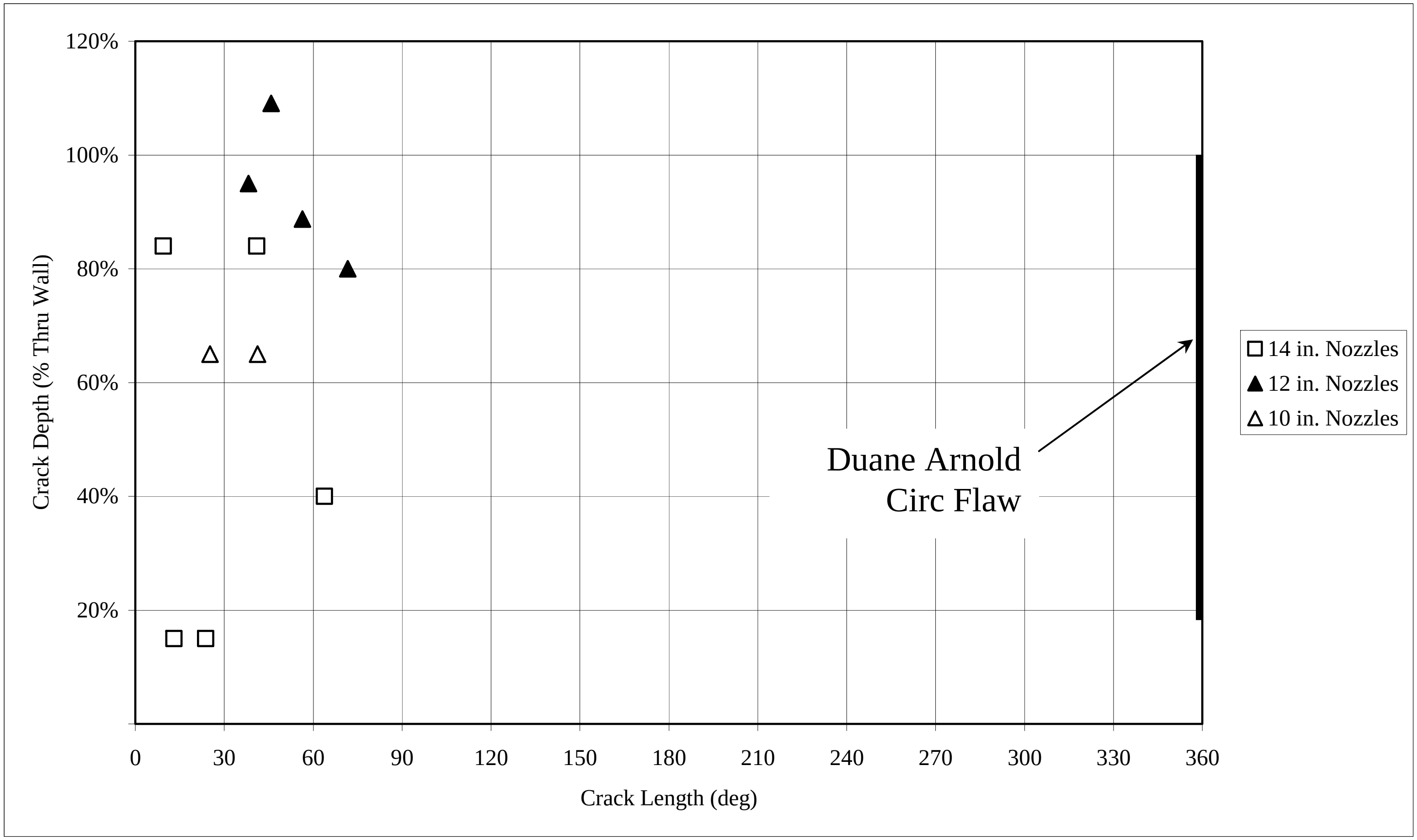




Validation Planning

BWR Piping Experience with Circ Cracks (MRP-113)

Arc Length and Depth for Circumferential Cracks in BWR Plants (Some Points Represent Multiple Cracks)



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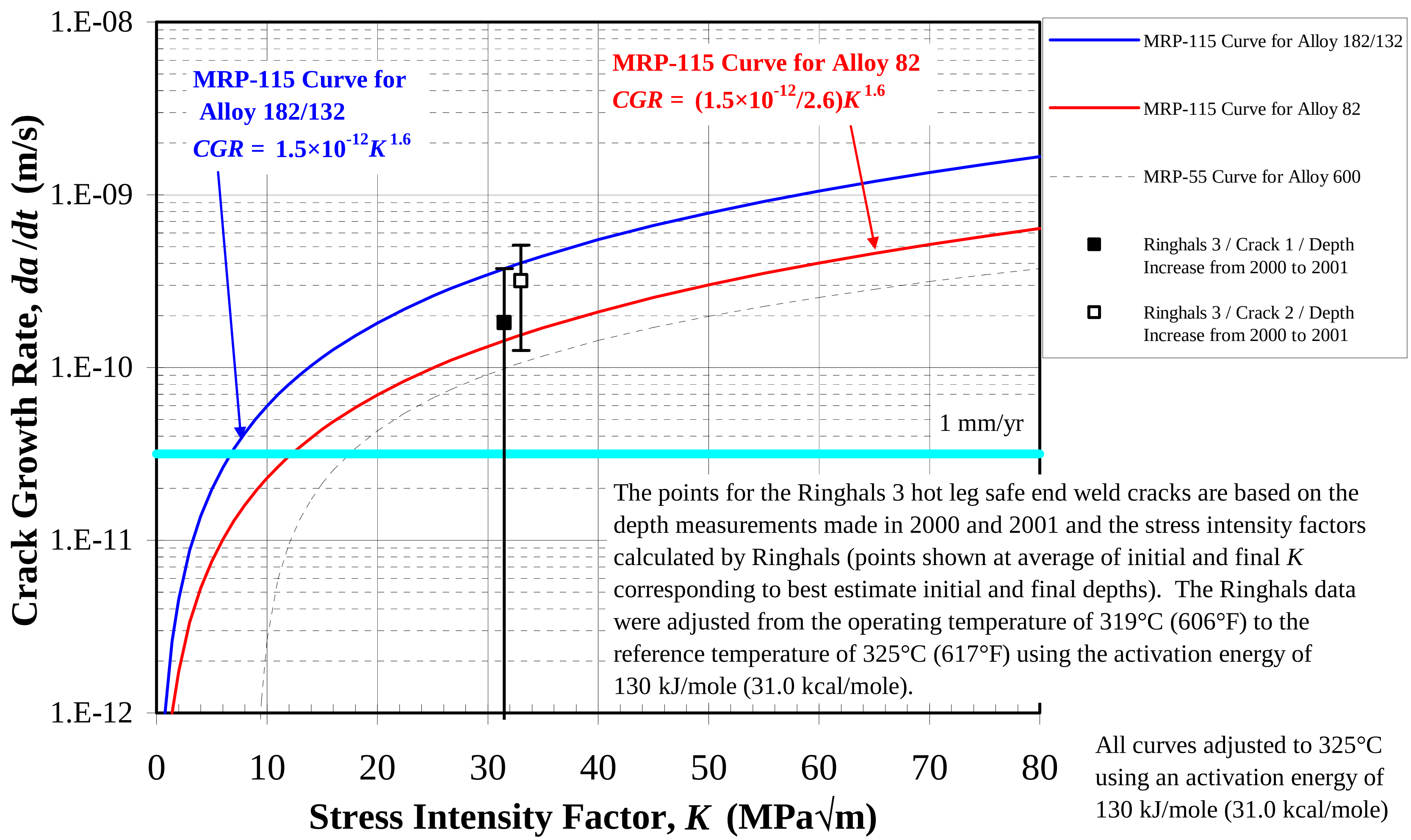
Validation Planning

Ringhals 3 Reactor Vessel Outlet Nozzle Alloy 82/182 Weld

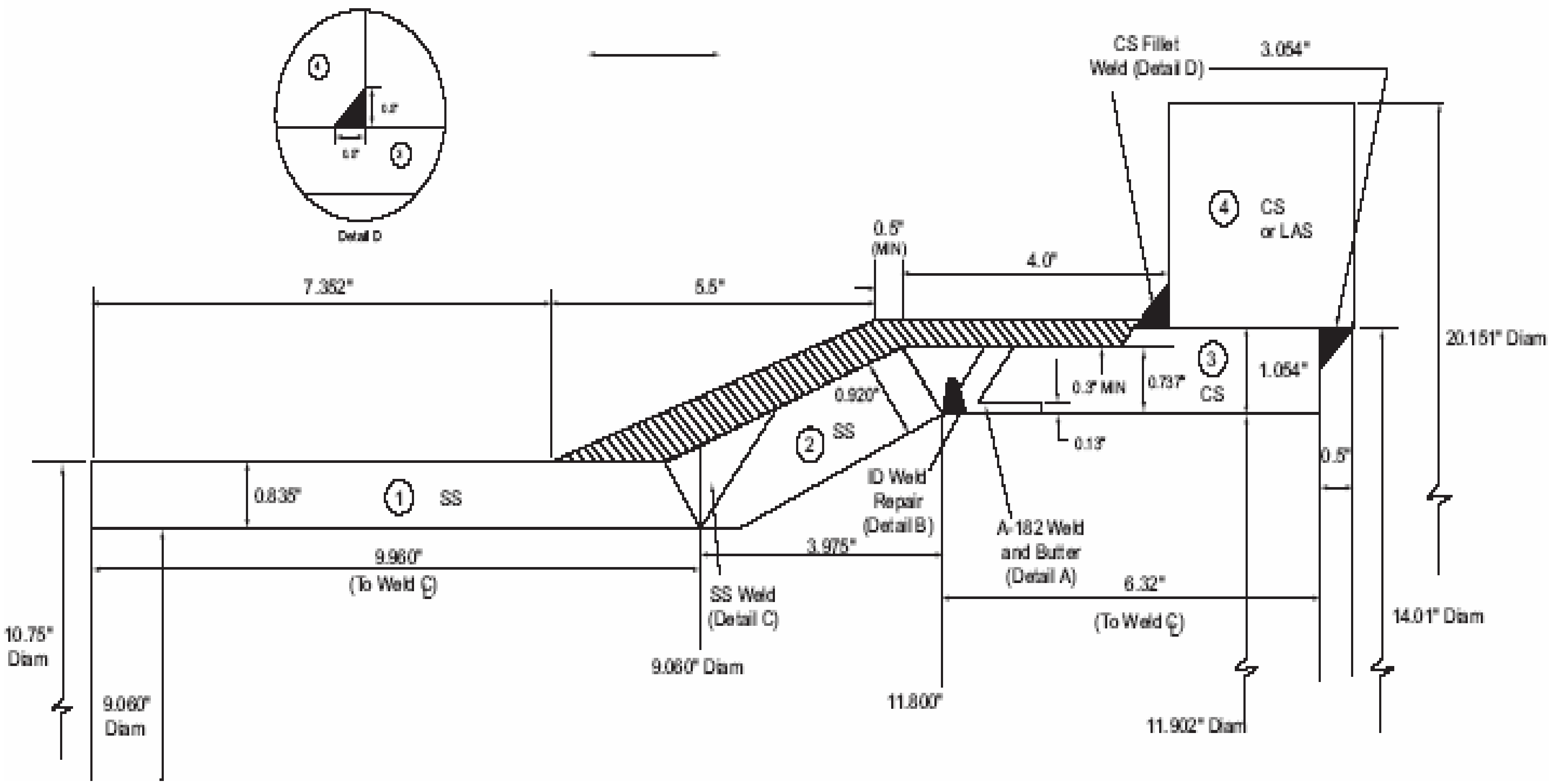


WRS Mockups
EPRI/SI Preemptive Weld Overlay (PWOL) Mockup

- EPRI and Structural Integrity Associates (SI) have recently completed a project that included fabrication of a mockup of a general vessel nozzle configuration
  - Attached to 10″NPS pipe
- The next 10 slides include the surface stress measurements made on the PWOL mockup before the weld overlay was applied
- This information may be useful as part of the validation studies

WRS Mockups

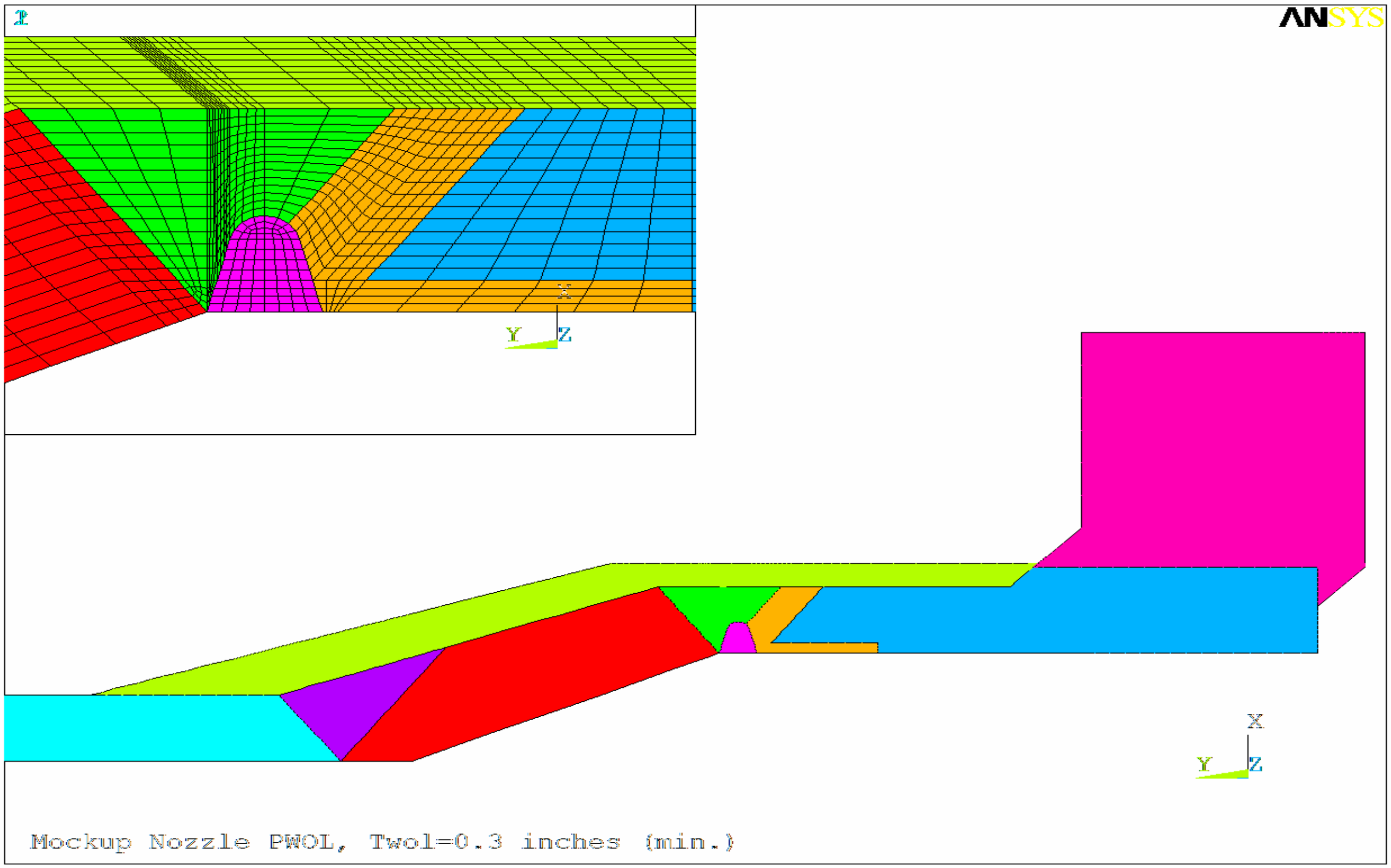
EPRI/SI Preemptive Weld Overlay (PWOL) Mockup Drawing



Structural Integrity Associates, Inc.

Dominion Engineering, Inc.

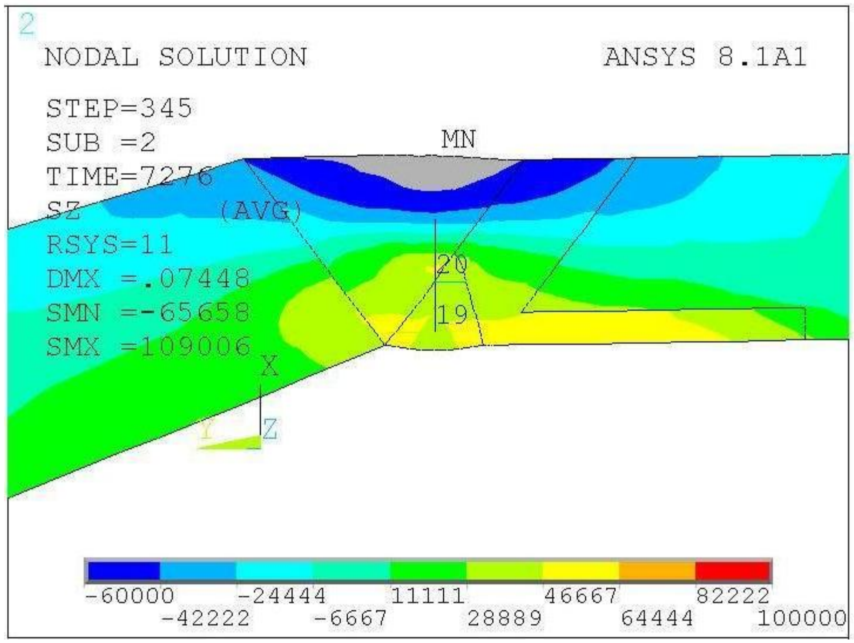
EPRI/SI PWOL Mockup
Finite Element Model



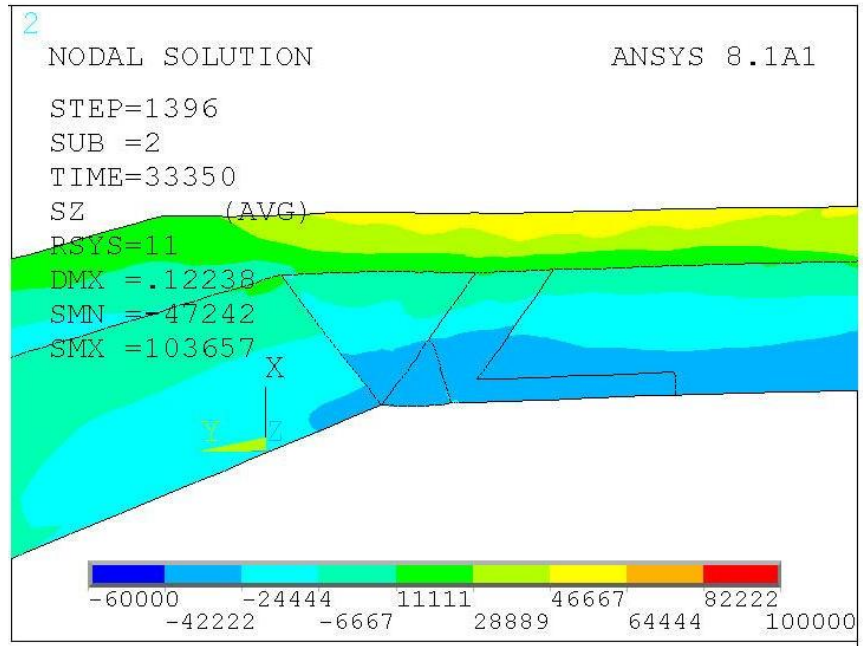
EPRI Structural Integrity Associates, Inc. Dominion Engineering, Inc.

EPRI/SI PWOL Mockup Analysis Results

Axial Residual Stresses



Pre-PWOL

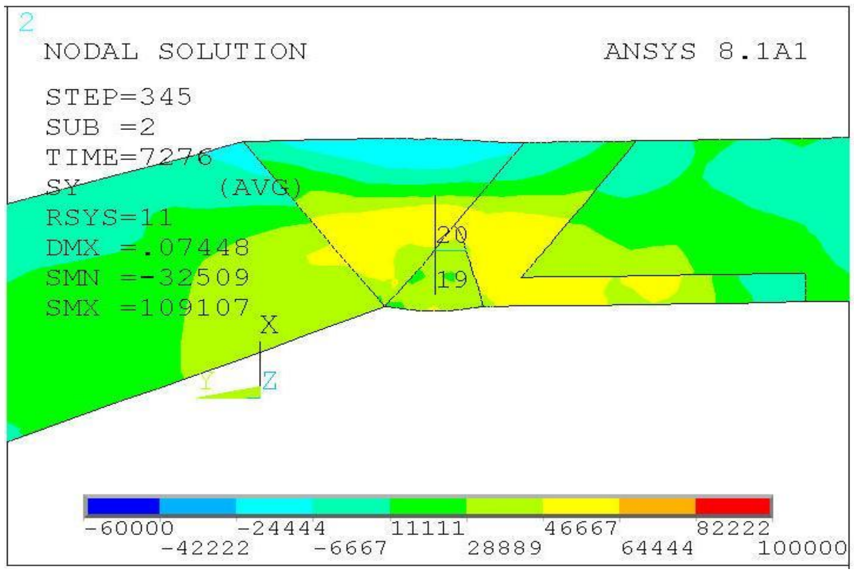


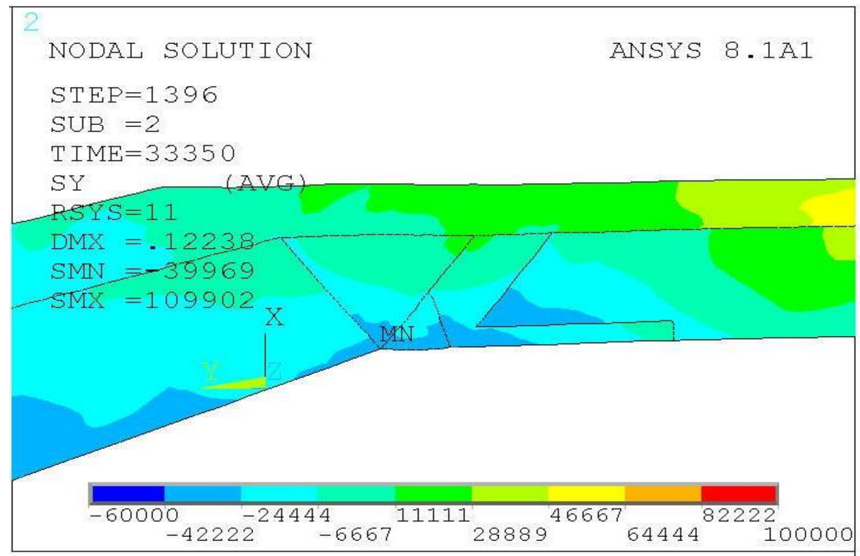
Post-PWOL

EPRI Structural Integrity Associates, Inc.

EPRI/SI PWOL Mockup Analysis Results

Hoop Residual Stresses

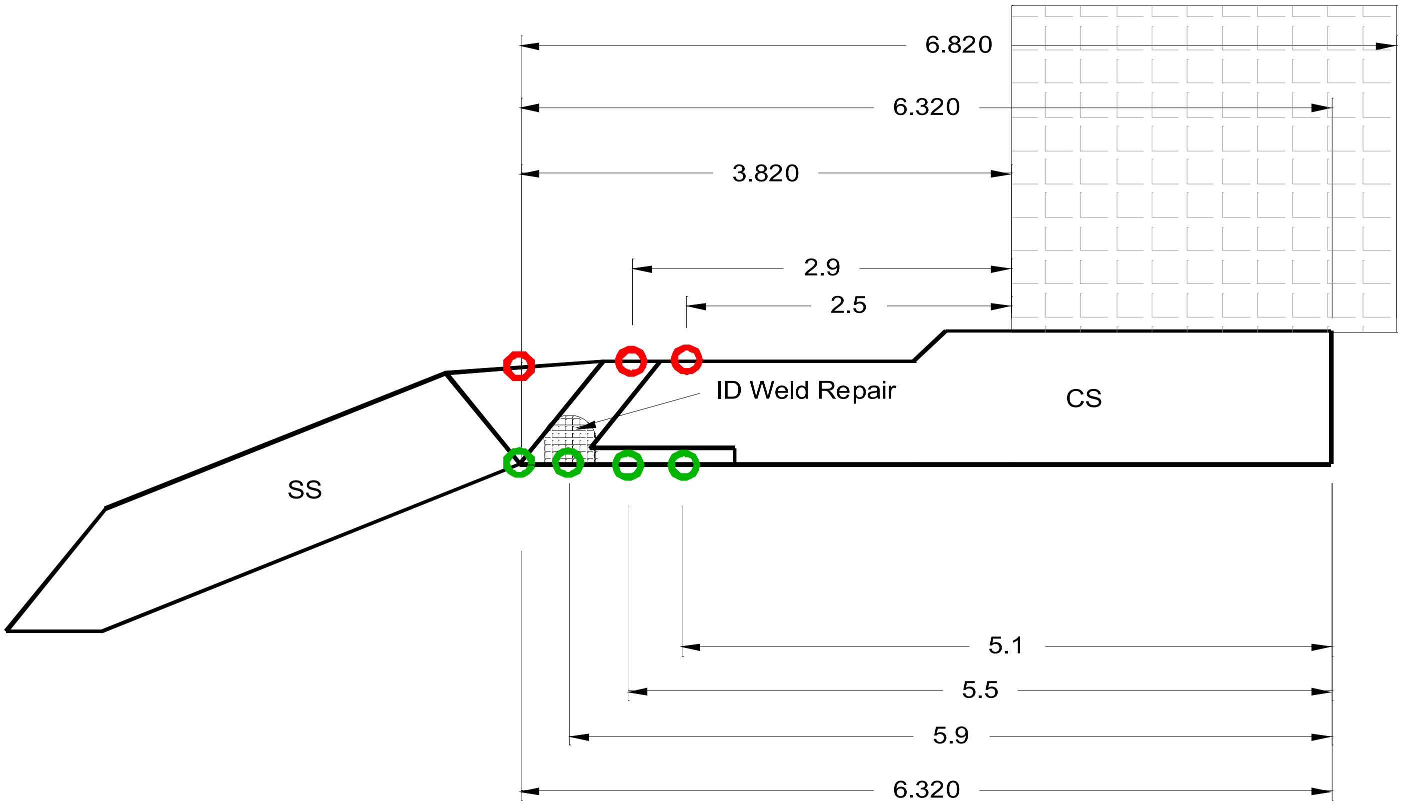




Pre-PWOL **Post-PWOL**

Structural Integrity Associates, Inc.

EPRI/SI PWOL Mockup
Residual Stress Measurements



Structural Integrity Associates, Inc.

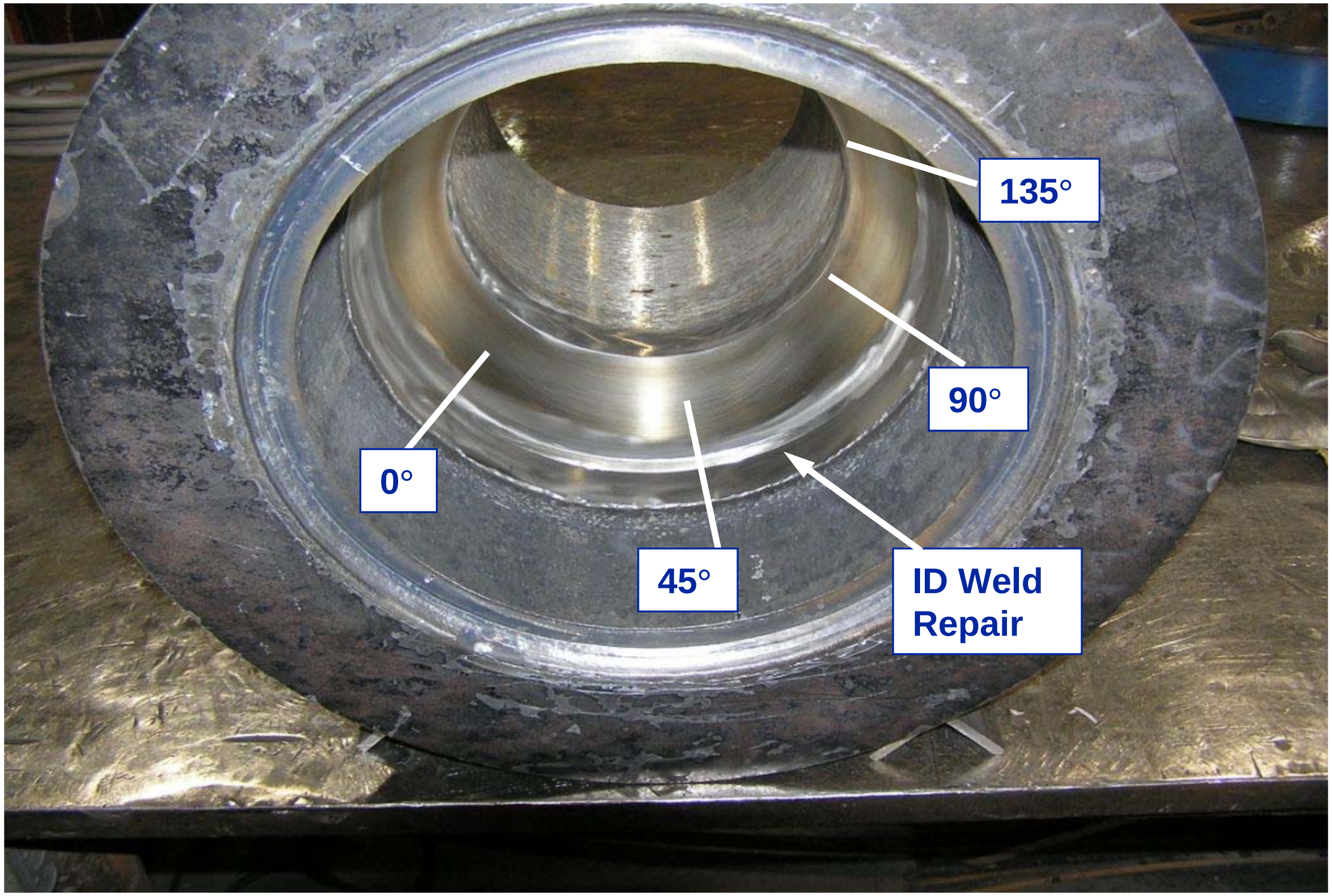
Surface measurements on ID and OD prior to Overlay Weld
@ 45 and 135-dgrees

OD @ weld centerline, center of butter, and one additional location .4-in. from weld butter.

EPRI

EPRI/SI PWOL Mockup

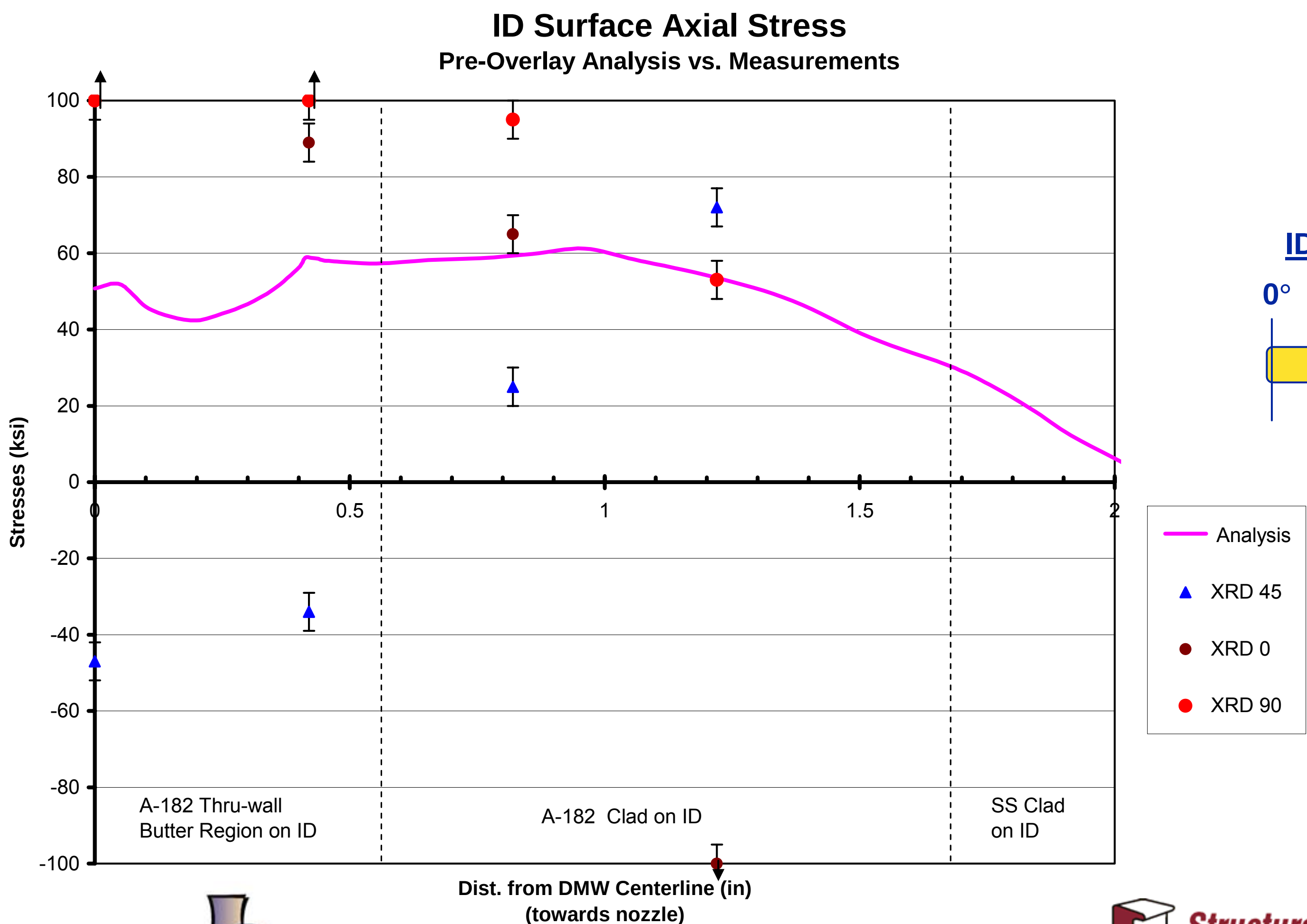
ID with 90° Weld Repair & XRD Measurement Locations

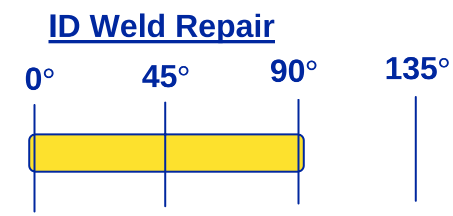


Structural Integrity Associates, Inc.

Dominion Engineering, Inc.

EPRI/SI PWOL Mockup
Axial Residual Stress Results: Pre-Overlay





Structural Integrity Associates, Inc.

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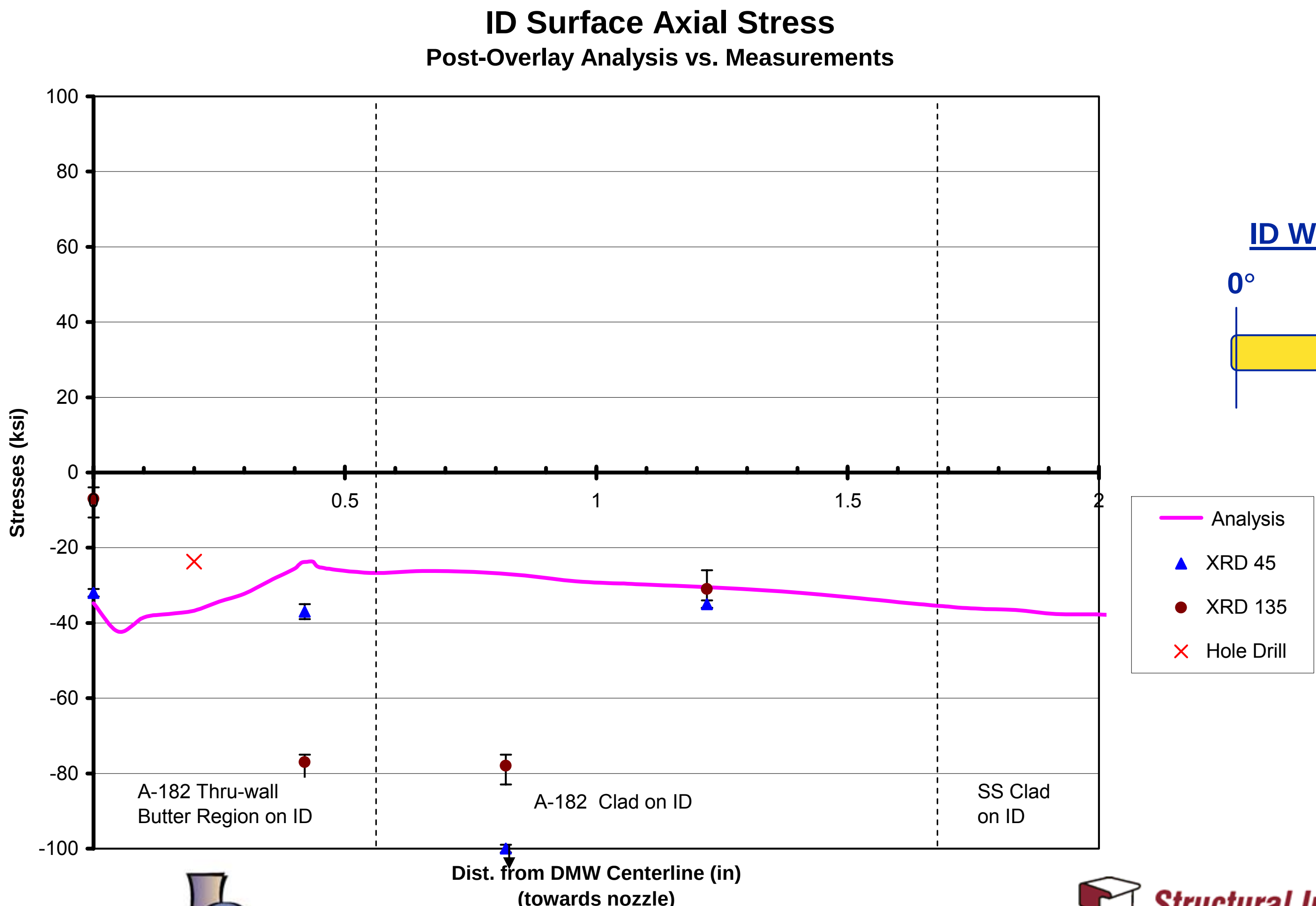
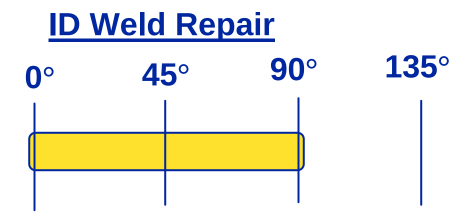
EPRI/SI PWOL Mockup
Axial Residual Stress Results: Post-Overlay

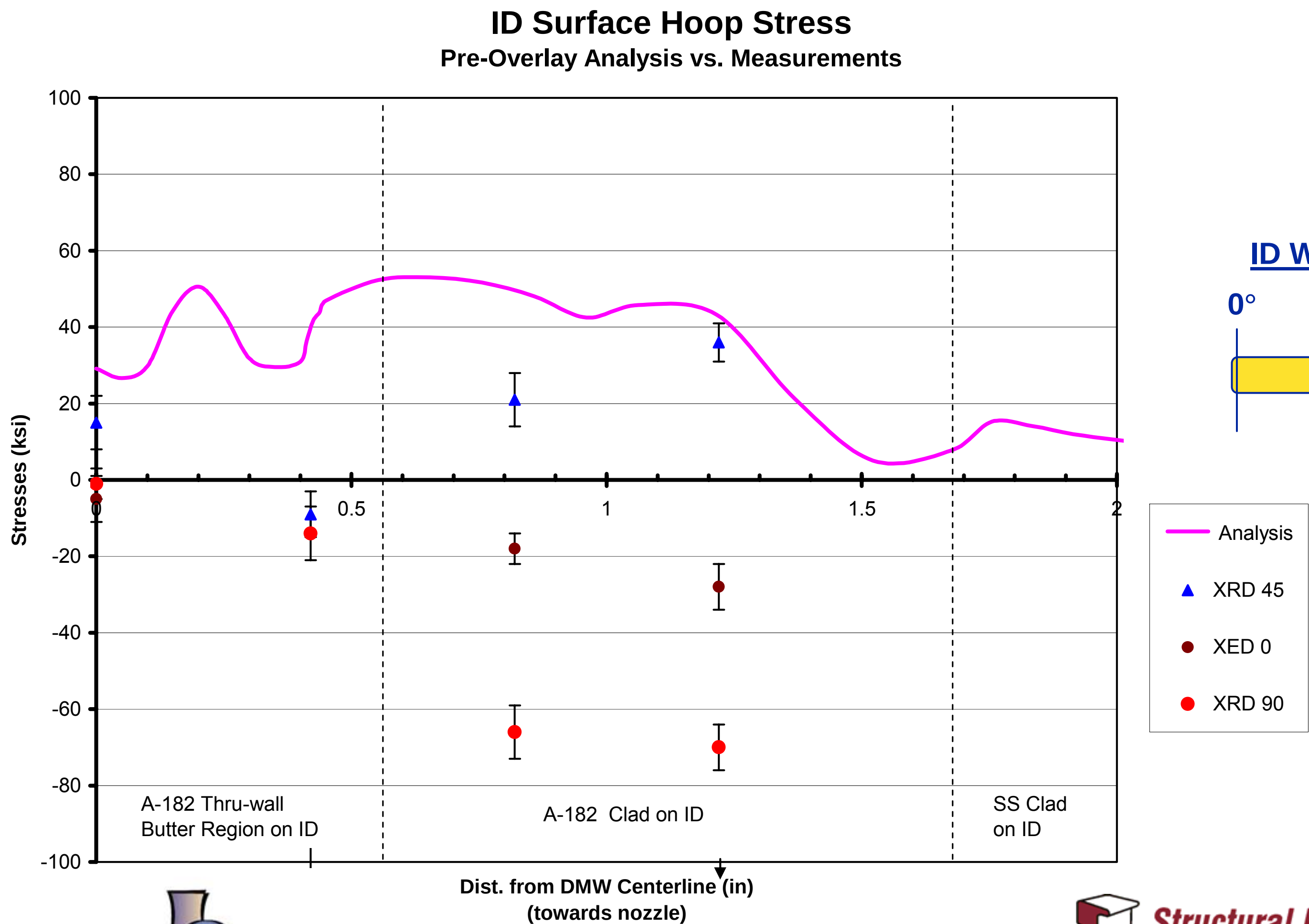


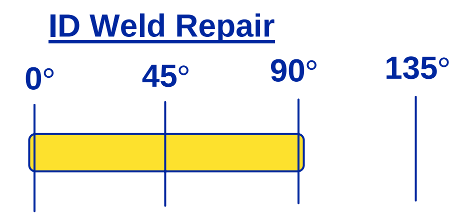


Structural Integrity Associates, Inc.

Dominion Engineering, Inc.

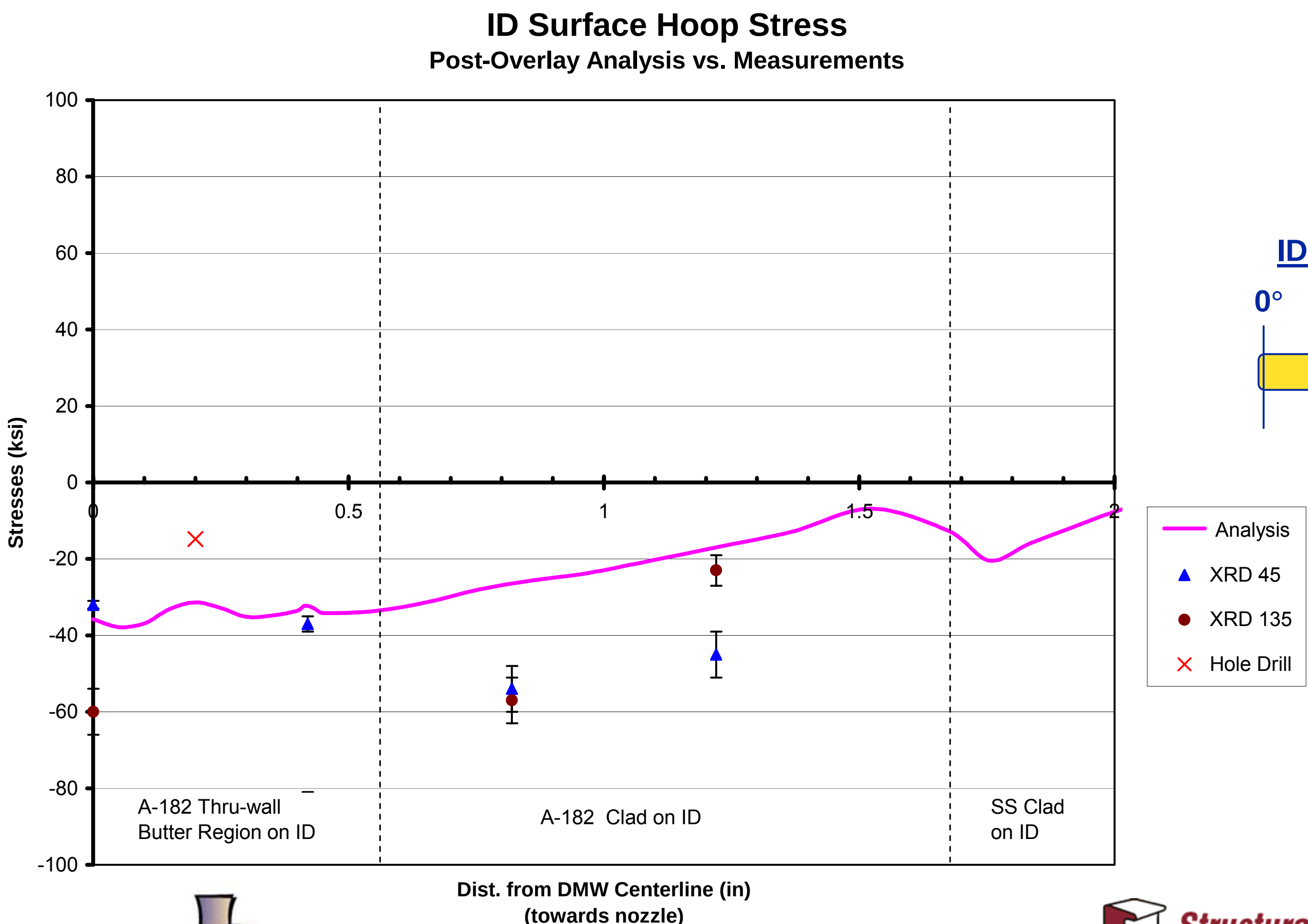
EPRI/SI PWOL Mockup
Hoop Residual Stress Results: Pre-Overlay

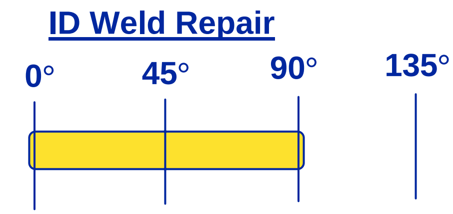




EPRI/SI PWOL Mockup

Hoop Residual Stress Results: Post-Overlay





EPRI

Structural Integrity Associates, Inc.

Dominion Engineering, Inc.

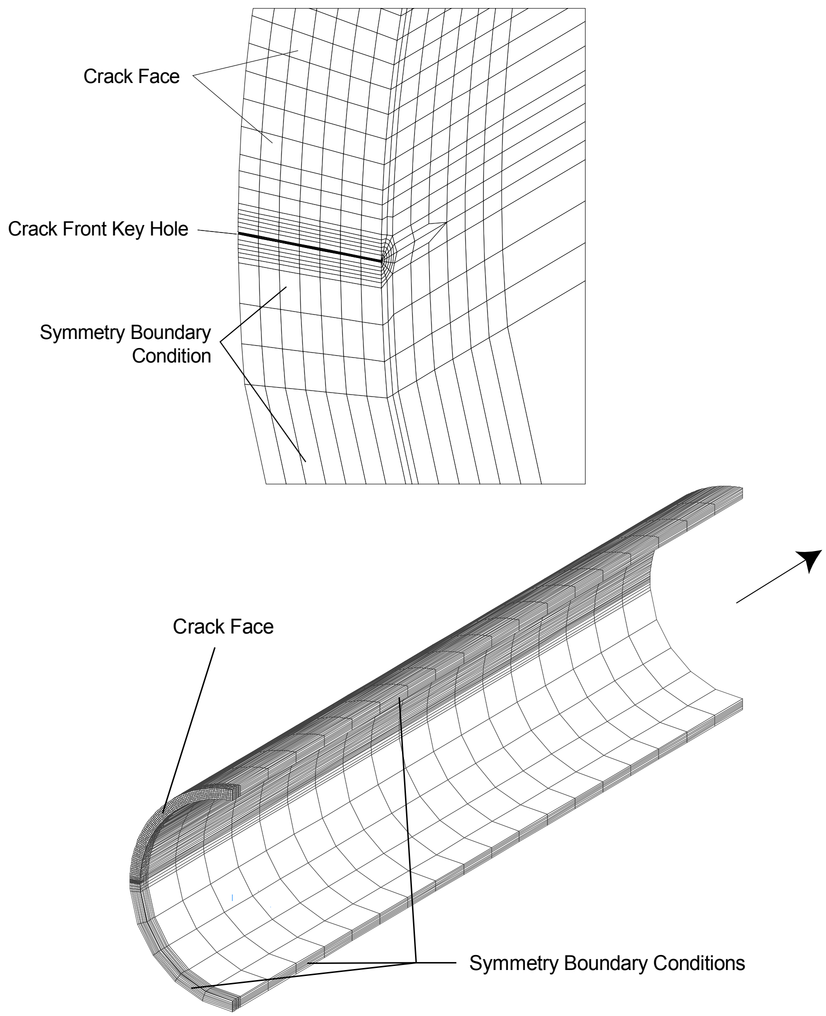
Benchmarking/Verification of SIF Calculation

Approach

- Benchmarking and verification tasks are in progress to verify that the FEACrack/ANSYS software including new modules is producing mathematically correct answers
- Surface and through-wall crack test cases are being compared against published solutions
  - Newman-Raju published solutions
  - EPRI Ductile Fracture Handbook (Zahoor) solutions
  - WRC Bulletin 471 (Anderson, et al.)
    - partial-arc semi-elliptical flaws
    - uniform-depth axisymmetric flaw and loading
  - Anderson solution for through-wall cracks in cylinders
  - Cases performed by NRC contractor (EMC2) for selected custom crack profiles
  - Other published solutions as available
- DEI is also performing general commercial software dedication of the FEACrack software per EPRI guidance

Benchmarking/Verification of SIF Calculation

Past Example 1: TW Circ Flaw in Cylinder

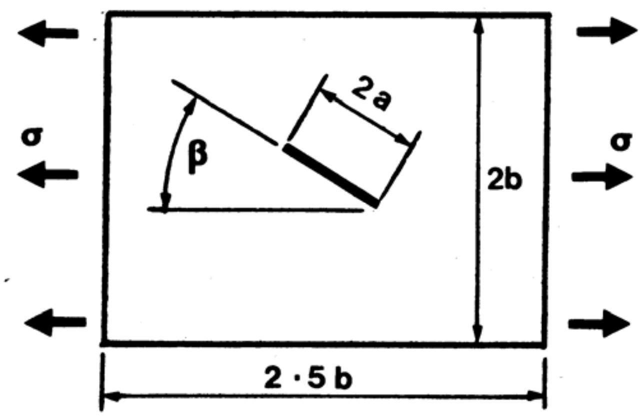


- Axially loaded through-wall flaw circumferential in cylinder
- SIF for model compared with EPRI Ductile Fracture Handbook results
  - R/t = 10, max arc = 180°
- Results agree within 10%

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

Benchmarking/Verification of SIF Calculation

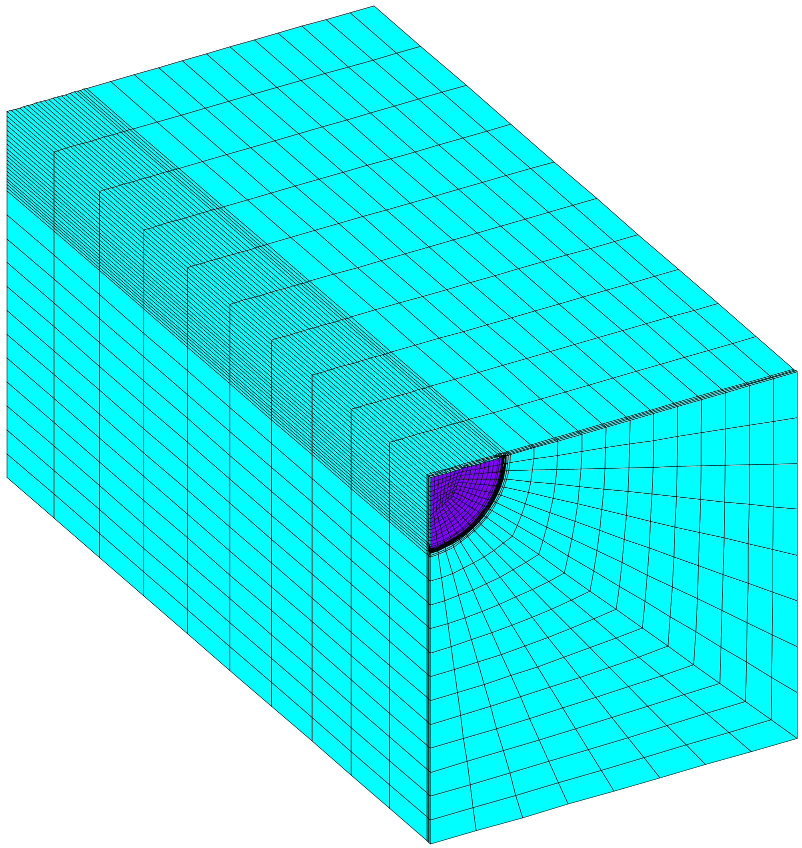
Past Example 2: Angled Crack in a Plate



- 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√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

Benchmarking/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√in
- FEA results = 69.6 ksi√in

Benchmarking/Verification of SIF Calculation

Verification and Validation Cases in Draft Phase I Calc

Table 1. 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

Table 2. 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

Table 3. 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

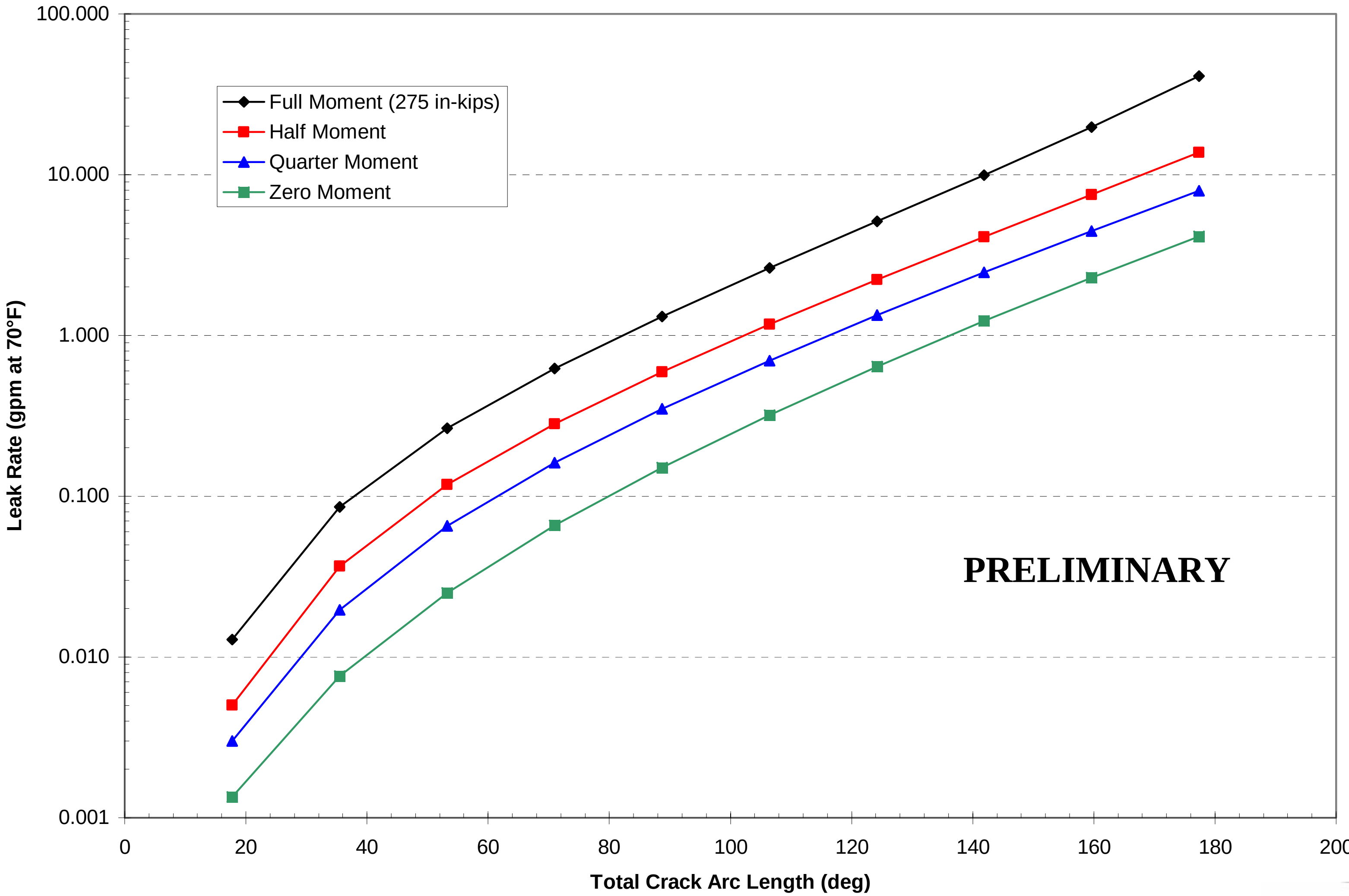
Leak Rate Calculations

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



Plans for Next Meeting(s)

- Previously tentatively scheduled meetings:
  - May 29 telecon: Telcon on Phase II progress
  - June 19 meeting: Present Phase II results

Meeting Summary and Conclusions

- Industry
- NRC