NRC/EOI Meeting to Discuss Requests for Alternative ANO1-R&R-005 & ANO1-R&R-006

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PROPOSED AGENDA FOR
THE MEETING BETWEEN ENTERGY AND NRC
ON RELIEF REQUEST 005 AND 006
AT ARKANSAS NUCLEAR ONE, UNIT 1
APRIL 16, 2004 AT NRC HEADQUARTERS

1. Introduction–NRC (Tom Alexion) 8:30 - 8:35

2. Discussion of the history of Relief Request 005 and 006 8:35 - until

3. Discussion of revised Relief Request 006

4. Discussion of the plan for the 6 repaired nozzles

5. Discussion of Revised Flaw Evaluation

   a. Flaw Model.
   b. Reactor head fabrication--weld residual stresses
   c. Analysis Assumptions, input parameters.
   d. Applicability of the input parameters (e.g., applied loads, boundary conditions) to the weld configuration.
   e. Step-by-step Methodology.
   f. Results.

6. Discussion of the Alternate Acceptance Criteria for the Revised Analysis.

   a. Technical justification
   b. Precedents
   c. Discuss why the ASME Code allowable is not applicable

7. Discussion of the Previous Flaw Evaluation–Entergy

   a. Discuss the differences between the previous flaw analysis in ANO- calculation 86-E-0074-156 and the revised flaw evaluation.
   b. Compare the previous analysis and the revised analysis.

8. Closing remarks regarding the Integrity of the repaired nozzles and future repairs

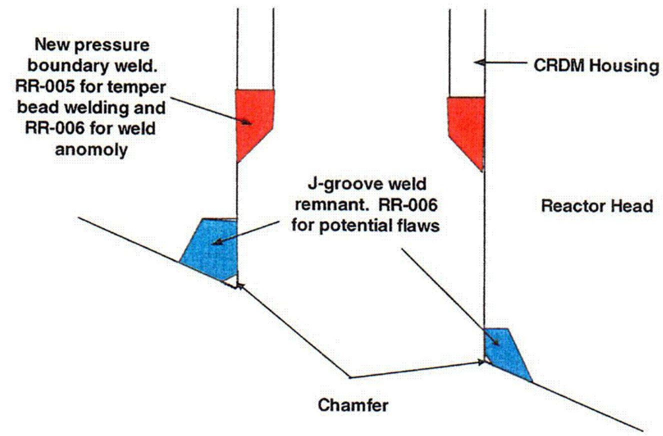
ENTERGY
ANO UNIT 1

CRDM Repair Relief Requests

CRDM Repair Relief Request

- Introduction
  - Bill James – Manager, Alloy 600 Project
  - William Sims – Supv./Technical lead, Alloy 600
  - Guy Davant – Corporate Licensing
  - Jai Brihmadesam – Corporate Engineering
  - Steve Lewis – Supervisor, Eng. Programs
  - Dick Mattson – Structural Integrity
  - Pete Riccardella – Structural Integrity
  - Bill Behnke – Framatome-ANP

CRDM Repair Relief Request



CRDM Repair Relief Request

- Current Status
  - 6 nozzles repaired during last outage (1R17) using Framatome repair configuration
  - Requested relief for the 6 repaired nozzles and for any repairs required during 1R18
  - Head is to be replaced during 1R19

History of ANO1-R&R-005 & ANO1-R&R-006

- ANO1-R&R-003 and ANO1-R&R-004
  - Applicable to 1R17
  - NRC provided verbal approval during 1R17; follow-up with written approval on 11/6/03.
- ANO1-R&R-005 and ANO1-R&R-006
  - Same as ANO1-R&R-003 and -004, respectively
  - Applicable to 1R18
  - Correspondence sent to NRC

CRDM Repair Relief Request

- Overview of New Analysis
  - CRDM/Head fabrication sequence
  - Assumed flaw configuration
  - Basis for evaluating the outermost nozzle
  - Methods for determining stresses & how they interact with the assumed flaw
  - Description of FEA models
  - Use of FEA vs. closed form solutions
  - Results of analysis

CRDM Repair Relief Request

- Acceptance of Analysis Results
  - Basis for current ASME Section XI rules
  - Acceptability for applying a reduced safety factor and how that aligns with ASME Section III and other provisions of ASME Section XI
  - Peer check by SIA using EPFM to verify margins

CRDM Repair Relief Request

- As requested:
  - Review Entergy responses to NRC RAIs
  - Address other NRC questions
- Closing Comments

ENTERGY OPERATIONS, INC.
ARKANSAS NUCLEAR ONE, UNIT 1
3rd 10-YEAR INTERVAL
REQUEST No. ANO1-R&R-006, Rev. 0

REFERENCE CODE:

The original code of construction for Arkansas Nuclear One, Unit 1 (ANO-1) is ASME Section III, 1965 Edition with Addenda through Summer, 1967. The components (including supports) may meet the requirements set forth in subsequent editions and addenda of the ASME Code incorporated by reference in 10 CFR 50.55a(b) subject to the limitations and modifications listed therein and subject to NRC approval. The codes of record for the repairs described within this request are the 1989 Edition of ASME Section III and 1992 Edition of ASME Section XI codes. ANO-1 is in its third (3rd) 10-Year Inservice Inspection interval.

I. System/Component(s)

a) Name of Component:

Reactor Pressure Vessel (RPV) head nozzles (There are 69 nozzles welded to the RPV head. This request applies to all 69 RPV head penetration nozzles, including the 6 that were repaired using the approved alternative ANO1-R&R-004 during the previous refueling outage.[1])

b) Function:

- The J-groove weld remnant left in place serves no function. It becomes nothing more than a remaining weldment attached to the RPV head.
- Any new repair welds serve as the pressure boundary weld for the RPV head nozzle and RPV head.

c) ASME Code Class:

The RPV head and RPV head nozzles are ASME Class 1.

d) Category:

Examination Category B-E, Pressure Retaining Partial Penetration Welds in Vessels; Item No. B4.12

II. Code Requirements

A. ASME Section XI (pertaining to the J-groove weld remnant)

Paragraph IWA-4310 requires in part that "Defects shall be removed or reduced in size in accordance with this Paragraph." Furthermore, IWA-4310 allows that "...the defect removal and any remaining portion of the flaw may be evaluated and the component accepted in

[1] Request for Alternative ANO1-R&R-004 (TAC No. MB6599) was approved by the NRC in a letter dated November 25, 2003.

accordance with the appropriate flaw evaluation rules of Section XI." The ASME Section XI, IWA-3300 rules require characterization of flaws detected by inservice examination.

Paragraph IWB-3420 requires the characterization of flaws in accordance with the rules of IWA-3300.

Subparagraph IWB-3142.4 allows the use of analytical evaluation to demonstrate that a component is acceptable for continued service. It also requires that components found acceptable for continued service by analytical evaluation be subject to successive examination during the next three inspection periods.

Paragraph IWB-3613 establishes acceptance criteria to be used for evaluating flaws in areas where bolt-up loads play a significant role (i.e., the RPV-to-head interface). IWB-3613(b) requires the use of a safety factor of √10 (3.16) to determine the stress intensity factor (SIF) of a flaw during normal operating conditions.

B. <u>ASME Section III (pertaining to the new repair weld)</u>

Section III Subsection NB-5330(b) states, "Indications characterized as cracks, lack of fusion, or incomplete penetrations are unacceptable regardless of length."

III. Proposed Alternative

Pursuant to 10 CFR 50.55a(a)(3)(i), Entergy proposes the following alternative to IWB-3420/IWA-3300, IWB-3142.4, IWB-3613(b), and NB-5330(b) as they pertain to the examination and evaluation of the repair weld and the remnant J-groove weld of the RPV head penetration nozzle that is not removed. Specifically, this alternative involves:

- Leaving a remnant of the J-groove weld in place following repair activities and operating with an SIF employing a safety factor of 2 rather than √10 (3.16) until the ANO-1 RPV head is replaced during the next refueling outage (1R19)
- Examining the repair weld

Each aspect is discussed below.

A. <u>The Remnant J-Groove Weld</u>

The planned repair for the subject RPV head nozzles does not include removing any cracks discovered in the remaining J-groove partial penetration welds. Therefore, per the requirements of IWA-4310, the cracks must be evaluated using the appropriate flaw evaluation rules of Section XI. No additional inspections can be performed to characterize the cracks due to the configuration of the nozzle and the weld. Thus, the actual dimensions of the crack cannot be fully determined as required by IWA-3300.

In lieu of fully characterizing any existing cracks, Entergy used worst-case assumptions to conservatively estimate the crack extent and orientation. The postulated crack extent and orientation were evaluated using the rules of IWB-3600. This evaluation, in conjunction with this request, justifies leaving the remnant weld in place without performing successive examinations in accordance with IWB-3142.4.

The evaluation also determined that the SIF of the postulated crack will not meet the acceptance criterion when using a safety factor of $\sqrt{10}$ required by IWB-3613(b). Rather than use this criterion, Entergy proposes to use a safety factor of 2.

B. Examining the Repair Weld

The new pressure boundary repair weld that connects the remaining portion of the RPV head nozzles to the low alloy RPV head contains a material "triple point." The triple point is located at the root of the weld where the Alloy 600 nozzle will be welded with Alloy 690 (52) filler material to the SA-533 Grade B, Class 1 Mn-Mo low alloy steel plate (See Figures 1 and 2). Experience has shown that during solidification of the Alloy 52 weld filler material, a lack of fusion (otherwise known as a welding solidification anomaly) area may occur at the root of the partial penetration welds.

Entergy is requesting relief from the requirement of NB-5330(b) regarding the potential lack of fusion at the root of the repair weld. If a weld triple point anomaly occurs in any of the repair welds, it will be evaluated in accordance with the appropriate flaw evaluation rules of ASME Section XI. Calculations have been completed to justify this welding solidification anomaly.[2]

IV. Basis and Justification for Proposed Alternative

Inspections of the RPV head will be performed in accordance with revised NRC Order EA-03-009, *Issuance of Order Establishing Interim Inspection Requirements for Reactor Pressure Vessel Heads at Pressurized Water Reactors*, dated February 20, 2004 and/or approved relaxation requests. These inspections may identify conditions that indicate a need to repair flaws discovered in the RPV head penetrations. The use of any of the alternatives permitted by the applicable ASME Codes for repairs will result in increased radiation dose with no compensating increase in quality or safety. The post-weld heat treatment (PWHT) parameters required by NB-4622 would be difficult to achieve on a RPV head in containment and would pose significant risk of distortion to the geometry of the RPV head and vessel head penetrations. In addition, the existing J-groove welds would be exposed to PWHT for which they were not qualified. This request applies to repair of any or all of the 69 RPV head penetrations.

A. The Remnant J-Groove Weld

The requirements of IWA-4310 allow two options for determining the disposition of discovered cracks. The subject cracks are either removed as part of the repair process or left as-is and evaluated per the rules of IWB-3600. The repair design specifies the inside corner of the J-groove weld be progressively chamfered from the center to outermost penetrations to maintain an acceptable flaw size. Section III paragraph NB-3352.4(d)(3) requires that the corners of the end of each nozzle to be rounded to a radius of ½ t_n or ¾ inch whichever is smaller. A 1/8-inch minimum chamfer considered equivalent to the radius specified in NB-3352.4(d)(3) will be incorporated on the bottom corner of the repaired RPV head nozzle penetrations in lieu of the radius. The radius is specified to reduce the stress concentration that might occur at a sharp corner; however, since the original partial penetration weld that remains in this area is analyzed assuming through-weld cracks exist therein the presence or absence of a radius or chamfer at this location is not significant with respect to stress

[2] See ANO Calculation E-86-0074-161 submitted to the NRC via Entergy letter CNO-2002-00054 dated November 26, 2002.

concentration. The primary purpose of the chamfer is to assure that any remaining cracks are no larger than those assumed for the analysis.

The assumptions of IWB-3600 are that the cracks are fully characterized to be able to compare the calculated crack parameters to the acceptable parameters addressed in IWB-3500. In the alternative being proposed, the acceptance of the postulated crack is calculated based on the two inputs of expected crack orientation and the geometry of the weld. Typically, an expected crack orientation is evaluated based on prevalent stresses at the location of interest. In these welds, operating and residual stresses are obtained using finite element analysis of the RPV head. Since hoop stresses will be the dominant stress as determined by calculations, it is expected that radial type cracks (with respect to the penetration) will occur. Using worst case (maximum) assumptions with the geometry of the as-left weld, the postulated crack will be assumed to begin at the intersection of the RPV head inner diameter surface and the RPV head nozzle bore and propagate slightly into the RPV head-to-butter interface. The depth and orientation are worst-case assumptions for cracks that may occur in the remaining J-groove partial penetration weld configuration.

The original nozzle-to-RPV head weld configuration is extremely difficult to UT due to the compound curvature and fillet radius as can be seen in Figures 1 and 2. These conditions preclude ultrasonic coupling and control of the sound beam in order to perform flaw sizing with reasonable confidence in the measured flaw dimension. Therefore it is impractical, and presently, the technology does not exist, to characterize flaw geometries that may exist therein. Not only is the configuration not conducive to UT but the dissimilar metal interface between the Ni-Cr-Fe weld and the low alloy steel RPV head increases the UT difficulty. Furthermore, due to limited accessibility from the RPV head outer surface and the proximity of adjacent nozzle penetrations, it is impractical to scan from this surface on the RPV head base material to detect flaws in the vicinity of the original weld. Entergy proposes to accept these flaws by analysis of the worst case that might exist in the J-groove. Since the worst case condition is to be analyzed as described below, no future examinations of these flaws is planned.

As previously discussed, after boring and removing the nozzle end, the remaining J-groove weld material will be chamfered to reduce the SIF.

Since the hoop stresses in the J-groove weld are generally about two times the axial stress at the same location, the preferential direction for cracking is axial, or radial relative to the nozzle. A radial crack in the Alloy 182 weld metal is postulated to propagate by primary water stress corrosion cracking (PWSCC) through the weld and butter, to the interface with the low alloy steel RPV head.

Detailed analyses, including residual stress evaluation and fracture mechanics, have been performed to establish the chamfer design that will result in an applied SIF, at the interface between Inconel alloy 600 butter weld and the low alloy steel reactor vessel head. This SIF exceeds the ASME Code Section XI allowable limit for normal-upset conditions using a safety factor of $\sqrt{10}$ per IWB-3613(b). The analyses were performed for an outermost nozzle penetration location (38.5°), which provides a bounding analysis for the other nozzles in the RPV head.

The residual stress analyses were performed using finite element methods that have been developed by Dominion Engineering Inc. for evaluating RPV head penetration J-groove weld residual stresses. The analyses are similar to those that supported various relaxation requests to NRC Order EA-03-009 that have been approved by the NRC staff.[3] The analyses simulate the original installation of the RPV head penetration nozzle. The process includes the installation of the butter layer followed by a post-weld heat treatment, J-groove welding of the nozzle followed by a Code hydro-test and subsequent steady state operation. Upon achieving ambient conditions the nozzle was removed. At this point, variations in chamfering depths were modeled, each model subjected to a normal heat-up followed by a steady state condition and then a cooldown to ambient. Two additional transient conditions, starting from an initial steady state condition, representing a reactor trip (normal and upset condition) and rod withdrawal (accident condition) were analyzed. This completes the full spectrum of the required analysis for performing finite element based fracture mechanics evaluations.

The fracture mechanics analysis uses a finite element model similar to that used in the residual stress analysis. The finite element model has a refined mesh that includes crack tip elements along the interface between the Inconel Alloy 600 butter weld and the low alloy carbon steel RPV head. This model simulates a fully cracked J-groove weld including the butter layer. The fracture mechanics analysis was performed using a linear elastic superposition method. Relaxing the residual stresses due to cracking was not utilized since the analysis used a linear elastic formulation. The SIFs were obtained at several locations along the postulated crack front. The stresses obtained from the residual and operating stress analysis were entered as crack face pressure. Reactor vessel internal pressure on the crack face was added to the distribution obtained from the stress analysis.

The stress plots at selected locations in the finite element stress analysis for non-steady state operation (i.e., heat-up, cool-down, reactor trip, and rod withdrawal) were reviewed to capture the maximum stress during the specific condition. In this manner, the SIF was maximized for use in fatigue evaluations.

The fracture mechanics analysis produced SIFs along the crack front for the conditions evaluated. The conditions evaluated were:

1) Normal steady state operation;

2) Normal heat-up from ambient condition;

3) Normal cool-down from steady state condition;

4) Reactor trip from steady state condition; and,

5) Rod withdrawal accident from steady state condition.

The obtained SIFs were compared to the applicable ASME Code Section XI IWB-3613(b) value for the specified condition of operation.

[3] See letters to Entergy from the NRC dated October 9, 2003, November 7, 2003, and November 12, 2003.

The NRC has documented its position for fracture mechanics analysis as follows:

> *So far, the NRC accepted only an approach of applying residual stresses directly on crack faces (i.e., as primary stresses) for various applications related to reactor pressure vessels, control rod drive mechanism (CRDM) penetrations, and in-core instrument (ICI) nozzles.*[4]

A summary of the results from fracture mechanics analysis, which were performed in accordance with this guidance, for the various assumed J-groove weld configurations is presented in Table 1. In this analysis, the fracture mechanics analysis was performed to evaluate the remnant J-groove weld by applying the stresses due to operating pressure, temperature gradients and residual stress effects on the crack face as primary stresses. Table 1 below shows that 14 of 16 values for maximum SIF obtained from these analyses exceed the currently allowable fracture toughness of 63.2 ksi√in in accordance with the √10 criterion of ASME Section XI, IWB-3613(b).

Table 1: Maximum SIF from Fracture Mechanics Analysis

J-groove Weld Remnant Configuration	Maximum Applied Stress Intensity Factor[1] (ksi√in)		
	Steady State Operation[2]	**Residual Stresses Only[3]**	**Operating Condition Only[4]**
No Chamfer	77.4 – Downhill 103.4 - Uphill	75.3 – Downhill 105.0 – Uphill	2.1-Downhill Note 5 – Uphill
Design Minimum Chamfer	80.0 –Downhill 94.4 - Uphill	78.6 – Downhill 99.3 – Uphill	1.4 – Downhill Note 5 – Uphill
Design Maximum Chamfer	79.4 – Downhill 84.8 - Uphill	57.8 – Downhill 68.7 – Uphill	21.6 – Downhill 16.1 Uphill
Theoretical Maximum Chamfer	65.2 – Downhill 62.5 - Uphill	67.9 – Downhill 69.1 – Uphill	Note 5 –Downhill Note 5 - Uphill

Notes:

1) *The applied SIF is based on considering the three conditions discussed in 2, 3, and 4, below.*
2) *The steady state condition is the combined SIF based on residual stress plus the steady state operating stresses (pressure and temperature).*
3) *The residual stress condition is based on the residual stress state after completion of the specific operation on the J-groove weld as indicated by the configuration column.*
4) *The operating condition is the difference between the steady state condition and the residual stress state. This column provides the SIF estimate due to the operating condition alone.*
5) *The SIF due to the residual stress is higher than at steady state operating condition.*

[4] See NRC letter, *Request for Additional Information Concerning WCAP-16180NP, Revision 0, "Operability Assessment for Combustion engineering Plants with Hypothetical Flaw Indications in Pressurizer heater Sleeves" (TAC No. MC1751)* from Mr. D. Holland, Project Manager, Office of NRR, to Mr. G. Bischoff, Manager, Owners Group Program Management Office, Westinghouse Electric Company.

The allowable SIF based on IWB-3613(b) is 63.2 ksi$\sqrt{in}$ for an upper shelf fracture toughness of 200 ksi$\sqrt{in}$. As shown in the Table 1, the applied SIFs are above the allowed minimum. The basis for the safety factor of "$\sqrt{10}$" in IWB-3613(b) can be found in Chapter 29 of the *ASME Companion Guide to the ASME Boiler and Pressure Vessel Code, Volume 2*, "Section XI Flaw Acceptance Criteria and Evaluation Using Code Procedures". The Guide states:

> *The acceptance criteria of IWB-3611 on flaw size were developed with the original purpose of maintaining the design margins of Section III. It is well known that the nominal factor of safety for normal and upset conditions is 3. Consider the general relationship between the stress intensity factor and the stress and flaw size at failure based on linear-elastic fracture mechanics, as noted in the following equation:*
>
> $$K_{Ic} = \sigma\sqrt{\pi a}$$
>
> *where K_{Ic} = the fracture toughness.*
>
> *It may therefore be deduced that a factor of safety of 3 on stress at failure is consistent with a factor of safety of 9 on flaw size. Code committees tend to prefer round numbers, so the value of 9 is rounded up to 10 to provide a safety factor slightly higher than the design safety factor.*

Therefore, the safety factor on the SIF, based on the above equation, results in a value of $\sqrt{10}$. The design safety factor value of 3 was based on the ultimate tensile strength of the ferritic material thereby limiting the applied general primary membrane stress (P_m) to be less than or equal to one-third of the material ultimate strength.[5]

In addition the design rules for Section III of the ASME Boiler and Pressure Vessel Code are defined for primary bending stress (P_b) and local primary membrane stress (P_L) to be lower than $1.5S_m$, which is approximately equal to the material yield strength. Further, the stress range when considering secondary stresses is increased by an additional factor of two to $3S_m$. This increase for local primary stresses then results in a nominal safety factor of two with consideration of bending and local stress effects. The limit on secondary stresses was included to prevent gross distortion of Code components.

The aspect of using different safety factors based on loading type was recognized in Appendix G to ASME Section XI. Although this appendix is for "hypothetical flaw analysis" to ensure safety against non-ductile fracture, its applicability to the evaluation of flaws potentially left in the CRDM J-groove welds is appropriate. The current evaluation assumes that the entire J-groove weld (including the butter) is cracked, which is analogous to postulating a maximum worse-case hypothetical flaw. In particular the guidance provided in paragraph G-2222 (Consideration of Membrane and Bending Stresses) notes that; *"Equation (1) of G-2215 requires modification to include the bending stresses which may be important contributors to the calculated K_I value at a point near a flange or nozzle."* Therefore, the controlling SIF equation, based on material toughness, was defined as:

$$K_{Ia} \geq 2(K_{Im} + K_{Ib})_{Primary} + (K_{Im} + K_{Ib})_{Secondary}$$

[5] See Chapter 6 of the *Companion Guide to the ASME Boiler and Pressure Vessel Code, Volume 1*, "Subsection NB – Class 1 Components".

where:

K_{Ia} = the available fracture toughness based on crack arrest for the corresponding crack tip temperature;

K_{Im} = the applied SIF due to membrane stress; and,

K_{Ib} = the applied SIF due to bending stress

In Appendix G, the distinction between primary and secondary stresses are recognized by using a safety factor of 2 on primary stresses and not requiring a safety factor on secondary stresses.

The safety factor considerations in the Code (Section III and Appendix G of Section XI) are based on the through-wall stress distribution, which is also the consideration for IWB-3600 of ASME Section XI. However, the safety factor presented in IWB-3613(b) considers the same safety factor for all stresses. This results in an overly conservative allowable SIF when the predominant loading mechanism is highly localized and due to residual stresses.

A more reasonable approach would be to utilize the philosophy of Appendix G to ASME Section XI and the safety factors utilized in Section III. This approach would result in the governing equation for SIF as:

$$K_{Ia} \geq 3.0(K_{Im} + K_{Ib})_{Primary} + 1.5\,(K_{Im} + K_{Ib})_{Secondary\ (or\ Residual)}$$

In the above equation the primary stresses would be those from operating pressure, which are the only non-displacement limited load on the top head. The secondary stresses would be those due to local structural discontinuity effects and thermal gradients. The safety factors applied are determined by multiplying those in Appendix G by a factor of 1.5. In this manner, the appropriate safety margin against non-ductile fracture would be maintained in a manner similar to that prescribed by Appendix G but with a higher safety factor. However, as shown in Table 1, this approach would provide a safety factor of 1.5, since the stresses are shown to be predominantly those due to residual stresses.

As an alternative, a safety factor applied to the residual stresses can be deduced from the structure of the safety factor for primary bending and primary local membrane stresses defined in ASME Section III. It was observed that the safety factor for these stresses was two-thirds of that for the general primary membrane stress. In addition, the fracture mechanics analysis for the current evaluation demonstrates that the predominant loading is due to the localized residual stress distribution, thereby, reducing the safety factor in IWB-3613(b) to a value of 2. Thus, the allowable SIF would be as follows:

$$K_{ITotal} \leq K_{Ia}/2$$

Using the results from the fracture mechanics analysis, for the maximum design chamfer case, the two approaches lead to the following result:

<u>Criteria 1</u>: $K_{Ia} \geq 3.0(K_{Im} + K_{Ib})_{Primary} + 1.5(K_{Im} + K_{Ib})_{Secondary\ or\ Residual}$

$$3(16.1)_{Operating\ Condition} + 1.5(68.7)_{Residual} = 151.4 \leq 200 \text{ Uphill Flaw}$$

$$3(21.6)_{Operating\ Condition} + 1.5(57.8)_{Residual} = 151.5 \leq 200 \text{ Downhill Flaw}$$

Alternate Criteria: $K_{ITotal} \leq K_{Ia}/2$

$$2(84.8) = 169.6 \leq 200 \text{ Uphill Flaw}$$

$$2(79.4) = 158.8 \leq 200 \text{ Downhill Flaw.}$$

The examples provided above show that there is a significant margin of safety against brittle fracture with either of the proposed acceptance criteria. In addition, the overall approach is conservative in that:

1. The fracture mechanics evaluation has been based on a hypothetical flaw that is assumed to exist in the entire J-groove.

2. The evaluation is based on linear elastic fracture mechanics principles with an assumed fracture toughness of 200 ksi√in. At elevated temperatures, the value of allowable fracture toughness is assumed, and the principles of elastic-plastic fracture mechanics, if used, could certainly demonstrate that significantly more margin would exist.

Entergy will submit a preliminary analysis report to the NRC staff to support their review of this request by April 13, 2004, and a final, completed analysis report by June 1, 2004.

An additional evaluation was performed to determine the potential for debris from a cracking J-groove partial penetration weld.[6] As noted above, radial cracks were postulated to occur in the weld due to the dominance of the hoop stress at this location. The possibility of occurrence of transverse cracks that could intersect the radial cracks was considered remote since there are no forces that would drive a transverse crack. The radial cracks would relieve the potential transverse crack driving forces. Hence, it is unlikely that a series of transverse cracks could intersect a series of radial cracks resulting in any fragments becoming dislodged.[7]

The cited evaluations provide an acceptable level of safety and quality in insuring that the RPV head remains capable of performing its design function for a sufficient number of heat-up/cool-down cycles to support one (1) operating cycle, with flaws existing in the original J-groove weld.

For the reasons described above, areas of J-groove welds containing flaws accepted by analytical evaluation will not be reexamined as required by IWB-3142.4. Although solidification anomalies may occur in the new repair weld, volumetric examination of these welds during a subsequent refueling outage is not required since Entergy plans to replace the ANO-1 RPV head during refueling outage 1R19, which is scheduled to begin during the fall of 2005.

Removing the cracks in the existing J-groove partial penetration welds would incur excessive radiation dose for repair personnel. With the installation of the new pressure boundary welds previously described, the original function of the J-groove partial penetration welds is no longer required. It is well understood that the cause of the cracks in the subject J-groove welds is PWSCC. As shown by industry experience, the low alloy steel of the RPV head impedes crack growth by PWSCC. Using an assumed worst-case crack size, the analysis

[6] See ANO Calculation E-86-0074-164 submitted to the NRC via Entergy letter CNRO-2002-00054 dated November 26, 2002.
[7] ANO Calculation E-86-0074-164, page 4

ensures that unacceptable crack growth into the RPV head does not occur within the next operating cycle. Thus, the RPV head can be accepted per the requirements of IWA-4310.

Based on extensive industry experience and Framatome-ANP direct experience, there are no known cases where flaws initiating in an Alloy 82/182 weld have propagated into the ferritic base material. The surface examinations performed associated with flaw removal during recent repairs at Oconee 1 and 3 on RPV head penetrations, Catawba 2 steam generator channel head drain connection penetration, ANO-1 hot leg level tap penetrations and the V. C. Summer hot leg pipe to primary outlet nozzle repair (reference MRP-44: Part I: Alloy 82/182 Pipe Butt Welds, EPRI, 2001 TP-1001491) all support the assumption that the flaws would blunt at the interface of the Ni-Cr-Fe weld to ferritic base material. Additionally, the Small Diameter Alloy 600/690 Nozzle Repair Replacement Program (CE NPSD-1198-P) provides data that shows PWSCC does not occur in ferritic pressure vessel steel. Based on industry experience and operation stress levels, there is no reason for service related cracks to propagate into the ferritic material from the Alloy 82/182 weld.

B. Examining the Repair Weld

Industry experience gained from earlier repairs of RPV head nozzles indicates that removal and repair of the defective portions of the original J-groove partial penetration welds were time consuming and radiation dose intensive. The prior repairs indicated that more automated repair methods were needed to reduce radiation dose to repair personnel. For the present ANO-1 repairs, a remote semi-automated repair method will be used for each of the subject nozzles. Using a remote tool from above the RPV head, each of the nozzles subject to this repair will first receive a roll expansion into the RPV head base material to insure that the nozzle will not move during subsequent repair operations. Second, a semi-automated machining tool from underneath the RPV head will remove the lower portion of the nozzle to a depth above the existing J-groove partial penetration weld. This operation will sever the existing J-groove partial penetration weld from the subject RPV head nozzles. Third, a semi-automated weld tool, utilizing the machine GTAW process, will then be used to install a new Alloy 690 pressure boundary weld between the shortened nozzle and the inside bore of the RPV head base material (see Figures 1 and 2). It was intended, as a part of the new repair methodology and to reduce radiation dose to repair personnel that the original J-groove partial penetration welds would be left in place. These welds will no longer function as pressure boundary RPV head nozzle to RPV head welds. However, the possible existence of cracks in these welds mandates that the flaw growth potential be evaluated.

In the case of the RPV head nozzle inside diameter (ID) temper bead repair, the term "anomaly" is applied to the unusual solidification patterns that result along the low alloy steel / Alloy 600/Filler Metal 52 interface of the repair weld. The anomalies originate along the low alloy steel (RPV head) to Alloy 600 (original nozzle) interface where melting occurs and generally extend back towards the center of the weld bead. These anomalies are typical for welds that involve a "lap joint" type interface, such as typical partial penetration weld geometries, in the weld joint design. Cross sections of nickel alloy welds made utilizing similar joint designs with Alloy 600 base materials and Alloy 82 filler metals have exhibited these phenomena consistently.

This phenomenon is compounded by the different solidification rates for the base materials and weld metal used in performing the repair. Other suspected factors in the anomaly occurrence are the size of the interface gap, gap cleanliness and position of the welding arc relative to the edge of the interface. The molten weld puddle simply freezes back to each side of the interface and follows the interface into the weld as solidification of the weld puddle take place. Weld root anomalies have been observed on several mockups with configurations simulating the repair weld. UT methods have been developed based on the characteristics of this anomaly so that verification to the prescribed acceptance criteria can be performed. The defect is treated like a crack, which is worst case. Two types of flaws are common in this area. The first is localized melting away of the feathered end of the beveled nozzle weld prep leaving occasional small voids. The second type flaw is caused due to an inherent problem during solidification of high Ni-Cr alloys in the presence of a notch such as a partial penetration weld. This type of flaw is in fact often called a "solidification anomaly" to differentiate it from what it is not – a crack.

IWA-4170 mandates that the repair design meets the original construction code or the adopted ASME Section III Code. As noted, the 1989 ASME Section III code has been adopted for qualification of the described repairs. Subsection NB-5330(b) stipulates that no lack of fusion area be present in the weld. A fracture mechanics analysis was performed to demonstrate compliance with Section XI of the ASME Code, for operating with the postulated weld anomaly described above.[8] The anomaly was modeled as a 0.1 inch "crack-like" defect, 360 degrees around the circumference at the "triple point" location. Full-size mockups using coupons from the Midland RPV head were metallographically evaluated. Both flaw types were occasionally found as expected and were less than the analyzed maximum allowed of 0.100 inch.[9]

Based on the fact that this anomaly is predictable as discussed herein, the anomaly can be detected by UT within the prescribed acceptance criteria and evaluated for fatigue and flaw growth using applicable ASME Sections III and XI methods. Therefore, the intent of the ASME Codes will be met. The ASME Section III analysis conservatively assumes a reduction in weld area (along the new weld-to-ferritic steel penetration fusion line) due to the anomaly and the ASME Section XI analysis assumes the anomaly is a crack-like defect.

Postulated flaws could be oriented within the anomaly such that there are two possible flaw propagation paths, as discussed below.

Path 1:

Flaw propagation path 1 traverses the RPV head tube wall thickness from the outside diameter (OD) of the tube to the ID of the tube. This is the shortest path through the component wall, passing through the new Alloy 690 weld material. However, Alloy 600 tube material properties or equivalent are used to ensure that another potential path through the heat affected zone (HAZ) between the new repair weld and the Alloy 600 tube material is bounded.[10]

[8] See ANO Calculations 86-E-0074-160 and 86-E-0074-161 submitted to the NRC via Entergy letter CNRO-2002-00054 dated November 26, 2002.
[9] ANO Calculation 86-E-0074-160, page 2 and ANO Calculation 86-E-0074-161, page 4
[10] ANO Calculation 86-E-0074-161, page 7

For completeness, two types of flaws are postulated at the outside surface of the tube. A 360 degree continuous circumferential flaw, lying in a horizontal plane, is considered to be a conservative representation of crack-like defects that may exist in the weld anomaly. This flaw is subjected to axial stresses in the tube. An axially oriented semi-circular outside surface flaw is also considered since it would lie in a plane normal to the higher circumferential stresses. Both of these flaws would propagate toward the inside surface of the tube.[11]

Path 2:

Flaw propagation path 2 runs down the outside surface of the repair weld between the weld and RPV head. A semi-circular cylindrically oriented flaw is postulated to lie along this interface, subjected to radial stresses with respect to the tube. This flaw may propagate through either the new Alloy 690 weld material or the low alloy steel RPV head material.[12]

The result of the analysis demonstrated that a 0.10-inch weld anomaly is acceptable for 25 years, which is beyond 2005 when the ANO-1 RPV head is scheduled to be replaced.[13] Residual stresses and stresses due to operation were considered. Significant fracture toughness margins were expected for both of the flaw propagation paths considered in the analysis. The minimum calculated fracture toughness margins were required to be greater than the required margin of $\sqrt{10}$ per ASME Section XI IWB-3612. Based on similar analysis, fatigue crack growth was expected to be minimal. The maximum final flaw size was small considering both flaw propagation paths. A limit load analysis was also performed considering the ductile Alloy 600/Alloy 690 materials along flaw propagation path 1. The analysis was required to show limit load margins for normal/upset conditions and emergency/faulted conditions greater than the required margins of 3.0 and 1.5 for normal/upset conditions and emergency/faulted conditions, respectively, per ASME Section XI, IWB-3642.[14]

Acceptance of the repair weld is based on this evaluation in accordance with ASME Section XI and demonstrated that for the intended service life of the repair, the fatigue crack growth is acceptable and the crack-like indications remain stable. These two findings satisfy the Section XI criteria but do not include considerations of stress corrosion cracking such as PWSCC. However, since the crack-like indications in the weld triple point anomaly are not exposed to the primary coolant and the air environment is benign for the materials at the triple point, the time-dependent crack growth from PWSCC is not applicable.

Eliminating the weld triple point anomaly requires use of an entirely different process than that proposed for use on ANO-1. The only qualified method currently available would involve extensive manual welding that would result in radiation doses estimated to be in excess of 30 REM per nozzle as compared to the 5 REM estimated for each nozzle repaired by the proposed process. Compliance with the specified Code requirements would result in excessive radiation exposure.

[11] Ibid.
[12] Ibid.
[13] ANO Calculation 86-E-0074-161, page 38
[14] ANO Calculation 86-E-0074-161, pages 22, 23, and 38

V. Duration of the Proposed Alternative

Entergy plans to replace the ANO-1 RPV head during Refueling Outage 1R19, which is scheduled to begin during the fall of 2005. Therefore, this request applies to:

- The previous operating cycle for the six (6) nozzles repaired in 1R17 using the Framatome technique, which was approved via alternative ANO1-R&R-004[15], and

- Upcoming Operating Cycle 19 for any of the 69 RPV head penetration nozzles that may be repaired during 1R18.

For the upcoming Operating Cycle 19, Entergy has evaluated the need to employ water jet conditioning and has determined such activities are not required. Entergy has performed an evaluation to determine the time for a postulated crack to grow 75% through-wall in the Alloy 600 nozzle material above the repair weld without employing water jet conditioning, as documented in Engineering Report M-EP-2004-002, Rev. 0.

The evaluation considers RPV head nozzles in the as-repaired condition and encompasses initiation and crack growth due to primary water stress corrosion cracking (PWSCC). This evaluation found that nozzle axial stresses are considerably lower than nozzle hoop stresses. Because of this, the likelihood of axial cracking is greater than the likelihood of circumferential cracking; therefore, only axial crack conditions were analyzed.

The analysis indicates that a crack will not grow to 75% through-wall in a time period of 4 years. This estimate is based on the following assumptions:

1. After PT and UT examination of the repaired ID surface, an undetected axial crack 0.157 inch long and 0.0679 inch deep (11% wall thickness) is assumed present.[16]

2. The crack growth rate under operating conditions was determined using the MRP-55 recommended curve modified for a crack growth amplitude (α) that represents B&W material data.[17]

3. The minimum wall thickness of the CRDM nozzle repair is 0.6175.[18]

4. Water jet conditioning is not applied.

Since Entergy plans to replace the ANO-1 RPV head during 1R19, which is prior to the end of 4 years, water jet conditioning is not necessary.

Given these expected results, the proposed inspection schedules given above, and the planned replacement date for the ANO-1 RPV head, Entergy believes the proposed alternatives to the ASME Code requirements are justified. The proposed alternatives are applicable to the repairs and examinations after repair to any ANO-1 RPV head nozzle.

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[15] Request for Alternative ANO1-R&R-004 (TAC No. MB6599) was approved by the NRC in a letter dated November 25, 2003.
[16] Engineering Report M-EP-2004-002, Rev. 0, Attachment 2 of Appendix C, page 2 of 17
[17] Engineering Report M-EP-2004-002, Rev. 0, Appendix B
[18] Engineering Report M-EP-2004-002, Rev. 0, Appendix A gives nozzle ID and OD dimensions.

VI. Implementation Schedule

This request will be implemented during upcoming refueling outage 1R18, which is scheduled to begin during the second quarter of 2004. Entergy plans to replace the ANO-1 RPV head during Refueling Outage 1R19, which is scheduled to begin during the fall of 2005.

VII. Conclusions

10CFR50.55a(a)(3) states:

> Proposed alternatives to the requirements of (c), (d), (e), (f), (g), and (h) of this section or portions thereof may be used when authorized by the Director of the Office of Nuclear Reactor Regulation. The applicant shall demonstrate that:
>
> (i) The proposed alternatives would provide an acceptable level of quality and safety, or
>
> (ii) Compliance with the specified requirements of this section would result in hardship or unusual difficulty without a compensating increase in the level of quality and safety.

Entergy believes that the proposed alternative provides an acceptable level of quality and safety because, as discussed in Section IV, above:

- Leaving a remnant of the original J-groove weld in place has been analyzed and shown to pose no adverse effect on plant operations.
- Although the SIF of a postulated crack in the J-groove weld remnant does not meet ASME Section XI requirements using a safety factor of $\sqrt{10}$, an SIF using a safety factor of 2 is commensurate with ASME Section III design requirements.
- Analysis has been performed demonstrating that a 0.1-inch weld anomaly in a new repair weld is acceptable for 25 years, which is beyond 2005 when the ANO-1 RPV head is to be replaced.

Therefore, Entergy requests that the NRC staff authorize this request pursuant to 10 CFR 50.55a(a)(3)(i).

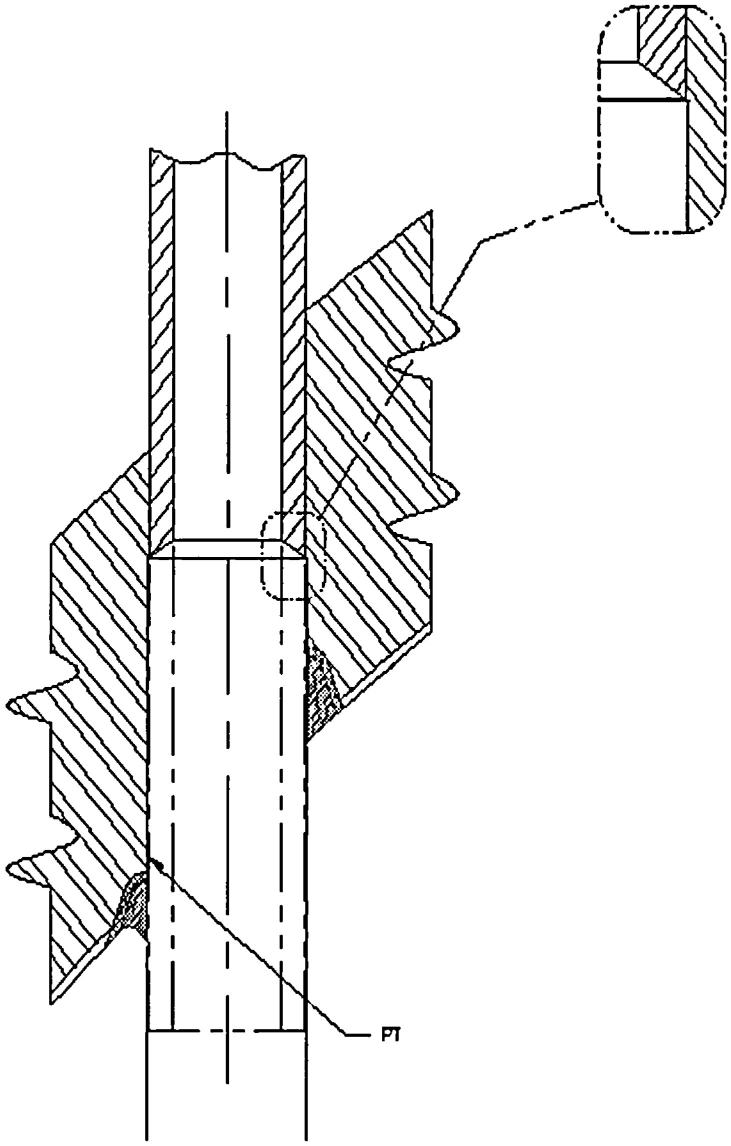


FIGURE 1
New ANO-1 RPV Head Nozzle

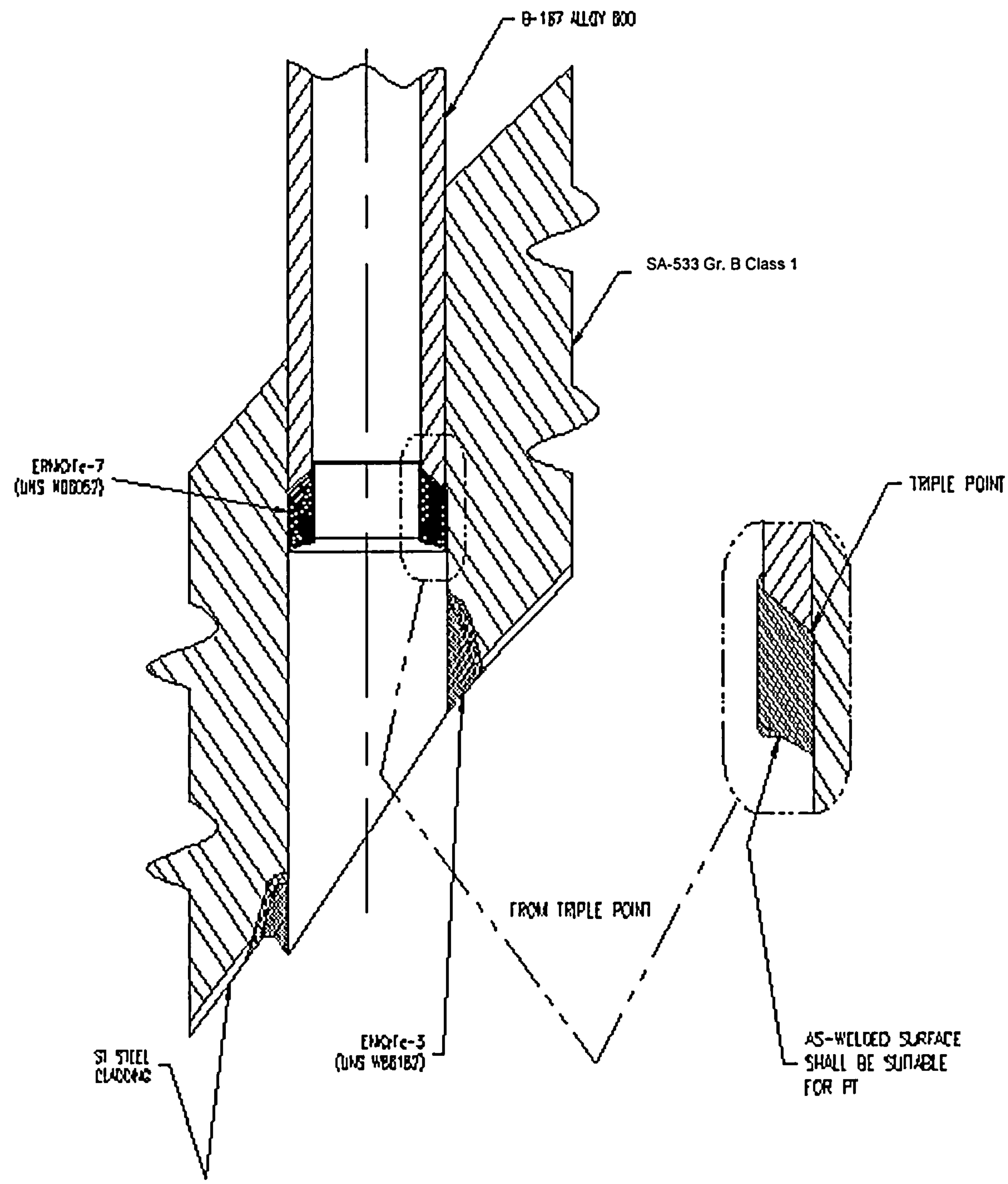


FIGURE 2
ANO-1 New RPV Head Pressure Boundary Welds

Technical Review Index

The information contained on the slides in Section V is obtained from the Technical Report contained in Section VII of this handout. For ease of reference, each subject is listed with a reference to the pages from the Technical Report (TR) that the information was derived.

Reactor Head Fabrication – Residual Stress Analysis (TR, Pages 6 – 16)

Basis for the Selection of Nozzle for Analysis (N/A)

Flaw Model and Hoop Stress Distribution through the Reactor Vessel Head (TR, Pages 17 – 19)

Fracture Mechanics Results for no Chamfer Case (TR, Page 9)

Fracture Mechanics Results for Design Minimum Chamfer Case (TR, Page 10)

Fracture Mechanics Results for Design Maximum Chamfer Case (TR, Page 10)

Fracture Mechanics Results for Theoretical Maximum Chamfer Case (TR, Page 11)

Comparison of all Fracture Mechanics Results (complete report)

Technical Basis for Entergy Method of Analysis (TR, Pages13 – 16, and 34)

ASME Code Considerations (TR, pages 36 – 37)

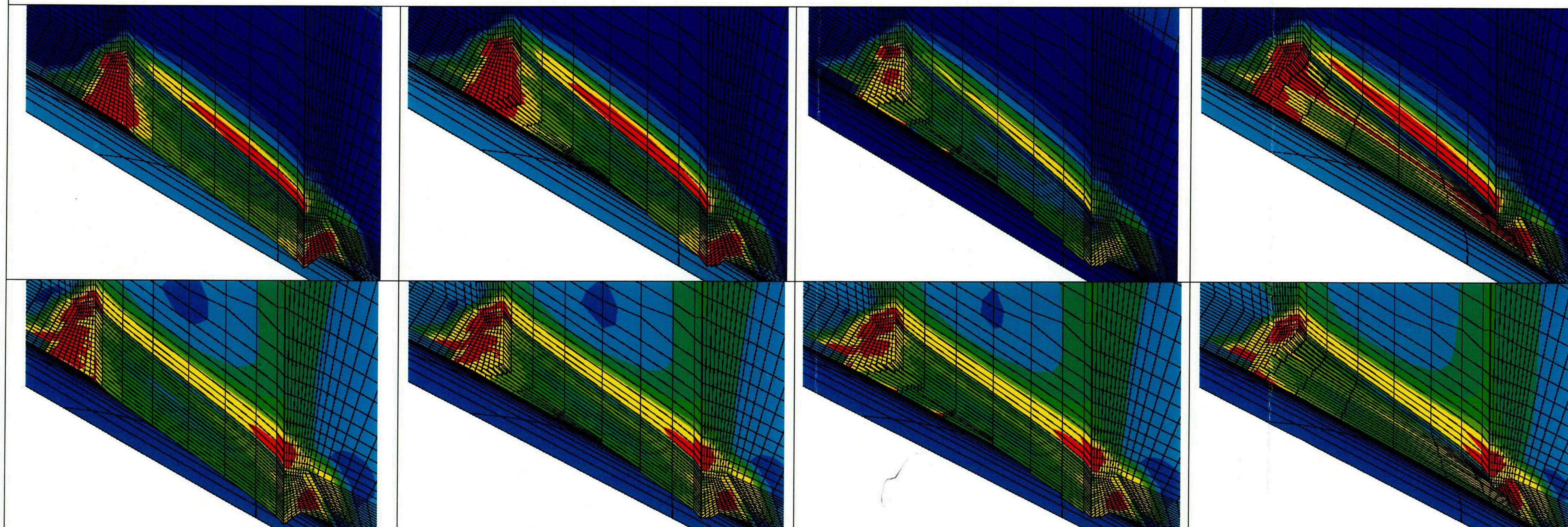
Reactor Head Fabrication – Residual Stress Analysis {Same methodology as used in previous Entergy relaxation requests}

- **Fabrication Sequence Modeled:**
  1) **J-groove butter layer (two element layers deposited in one weld simulation)**
  2) **Post Weld Heat Treatment (simulated fabrication PWHT)**
  3) **Nozzle welded to Reactor Vessel Head (Two equal volume weld simulation passes)**
  4) **Pre-operational hydro-test as done in practice**
  5) **Operating sequence for normal steady state operation**
  6) **Counterbore, ID Temper bead welding and install chamfer**
- **Finite Element Model:**
  1) **3-D Solid brick elements**
  2) **Tube material modeled with monotonic stress-strain curve (work hardening included)**
  3) **Weld material modeled as elastic-perfectly plastic**

Definition of Terms

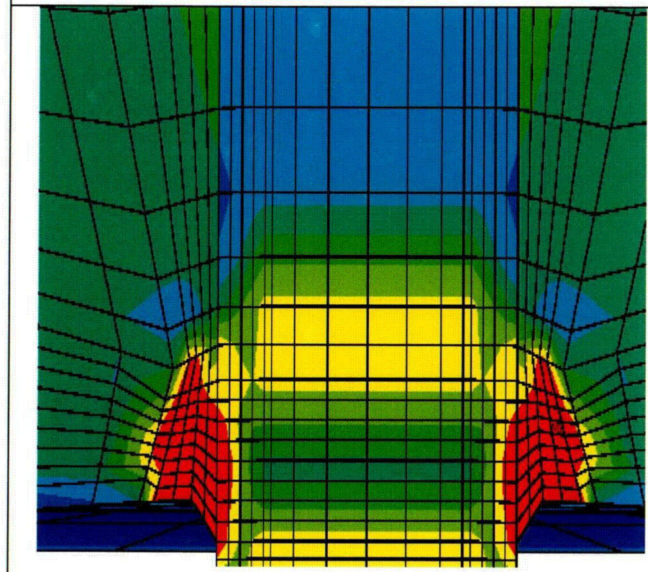
Residual Stress Only: Residual Stress at Ambient Temperature

Steady State Condition: Residual Stress$_{\text{@ Operating Temperature}}$ +Operating Stresses$_{\text{Pressure \& Thermal}}$

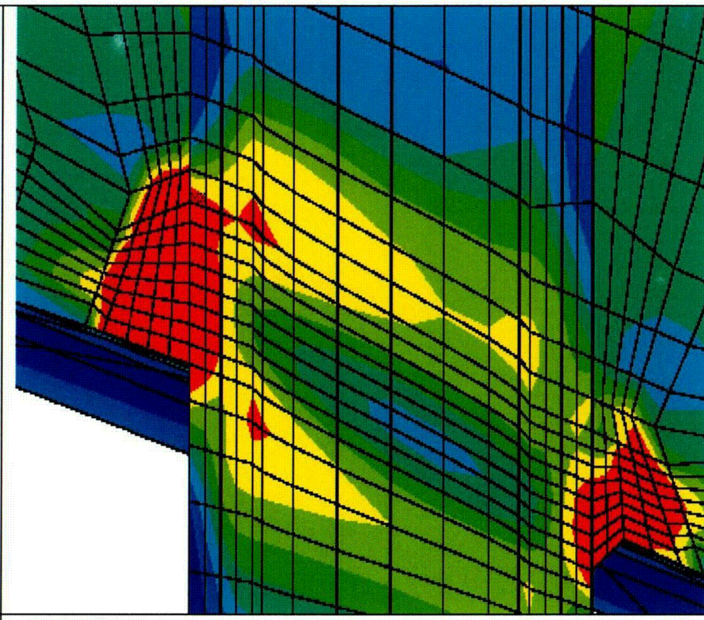


No Chamfer case. Upper: Residual stress only; Lower: Steady State Condition;	**Design Minimum Chamfer case.** Upper: Residual stress only; Lower: Steady State Condition;	**Design Maximum Chamfer case.** Upper: Residual stress only; Lower: Steady State Condition;	**Theoretical Maximum Chamfer case.** Upper: Residual stress only; Lower: Steady State Condition;

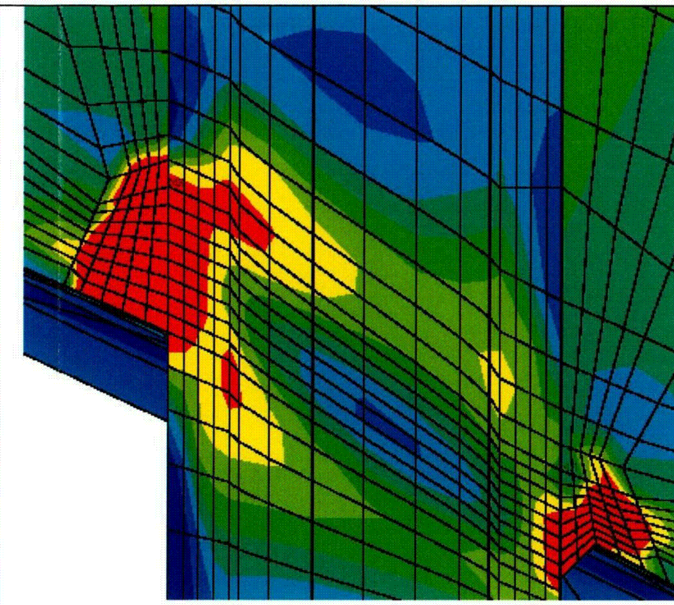
Basis for the Selection of Nozzle for Analysis



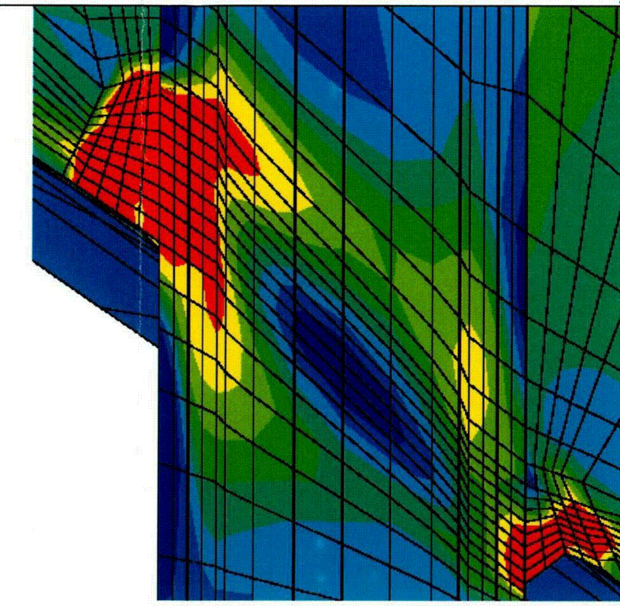
"0°" Penetration Equal Weld Size.
Weld Size Uphill:
Bore ID 1.61" RVH ID 1.11"



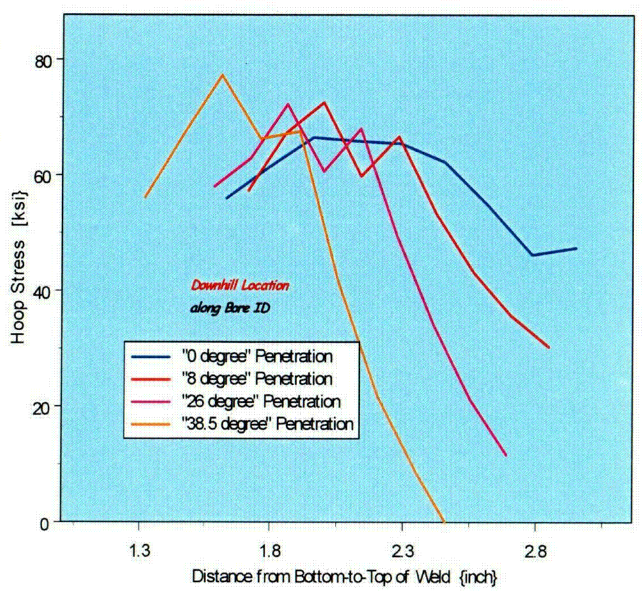
"18.2°" Penetration Uphill weld larger than Downhill.
Weld Size Uphill:
Bore ID 1.59" RVH ID 1.11"
Weld Size Downhill:
Bore ID 1.4" RVH ID 1.11"



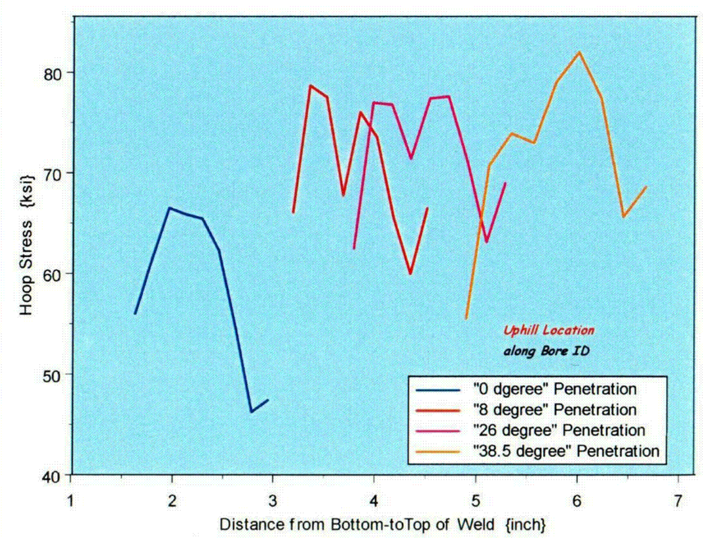
"26.2°" Penetration Uphill weld larger than Downhill.
Weld Size Uphill:
Bore ID 1.76" RVH ID 1.17"
Weld Size Downhill:
Bore ID 1.37" RVH ID 1.10"



"38.5°" Penetration Uphill weld larger than Downhill.
Weld Size Uphill:
Bore ID **2.22**" RVH ID **1.33**"
Weld Size Downhill:
Bore ID **1.6**" RVH ID **1.18**"



Downhill comparison of hoop stress along bore ID.



Uphill comparison of hoop stress along bore ID.

Selection of Bounding Nozzle for Analysis

- **Weld size increases with penetration angle.**
- **Larger weld size results in larger initial flaw size.**
- **Peak stress increases with penetration angle.**

Selection Basis

- **Largest initial flaw size.**
- **Highest hoop stress.**

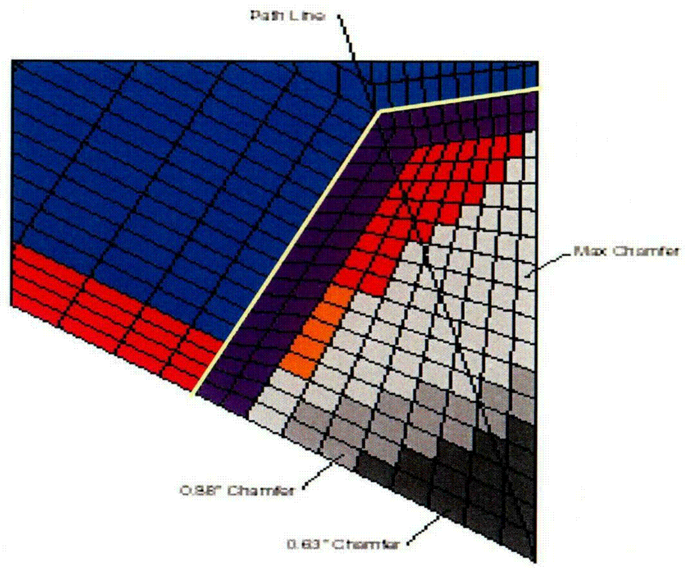
Nozzle Selected

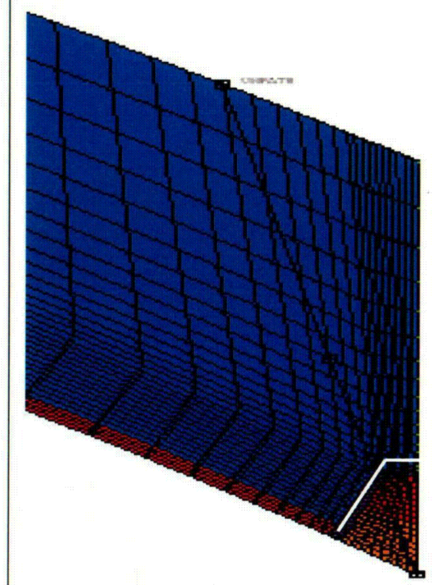
38.5° penetration

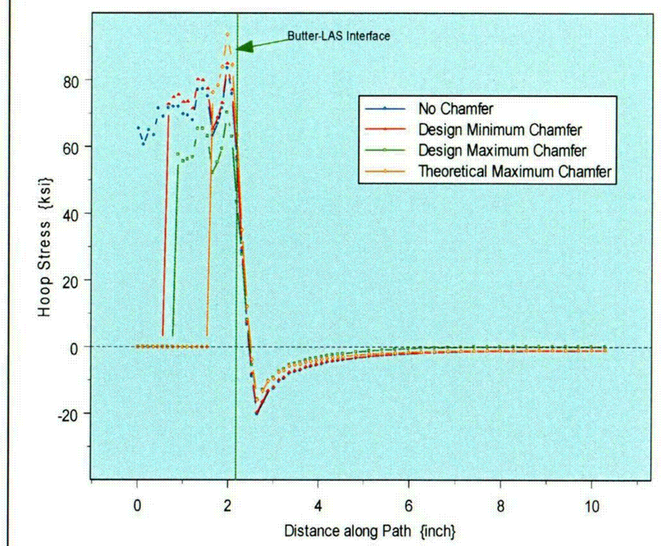
C03

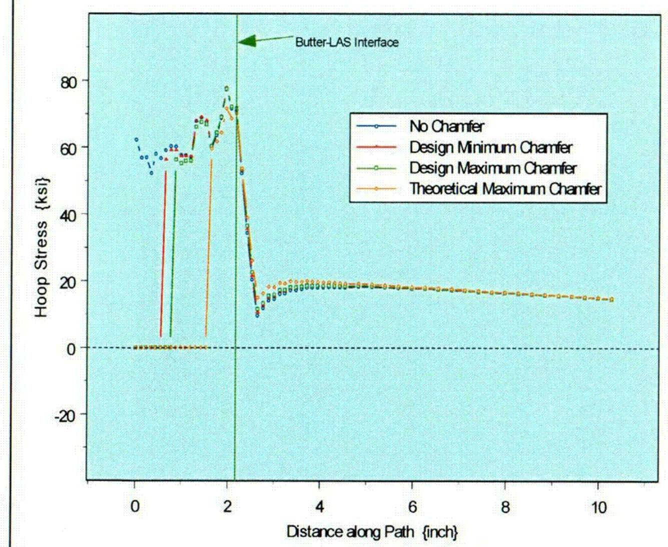
Flaw Model and Hoop Stress Distribution through the Reactor Vessel Head

UPHILL

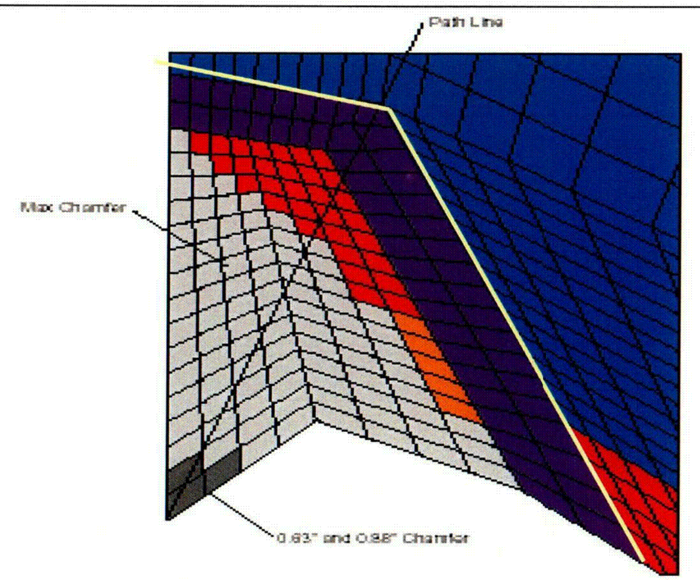


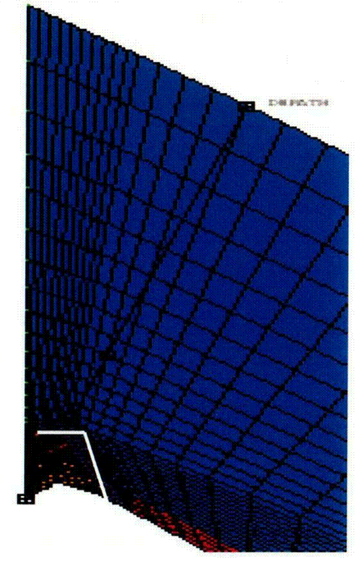


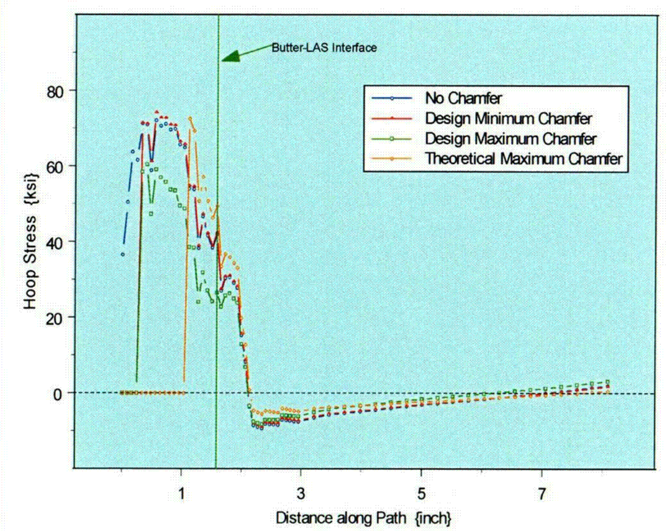


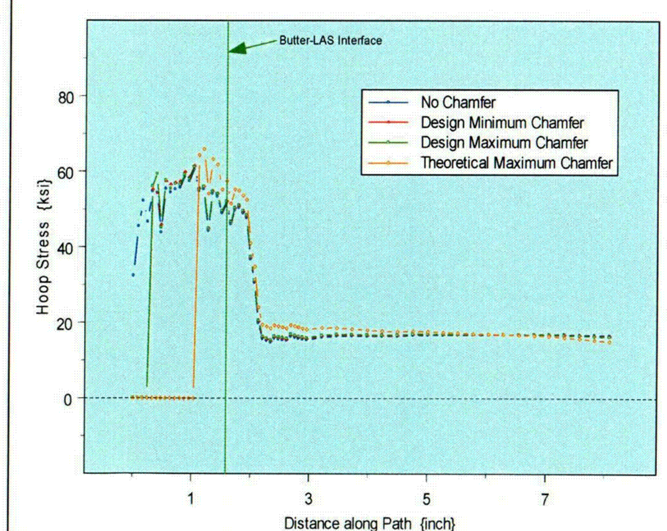


DOWNHILL



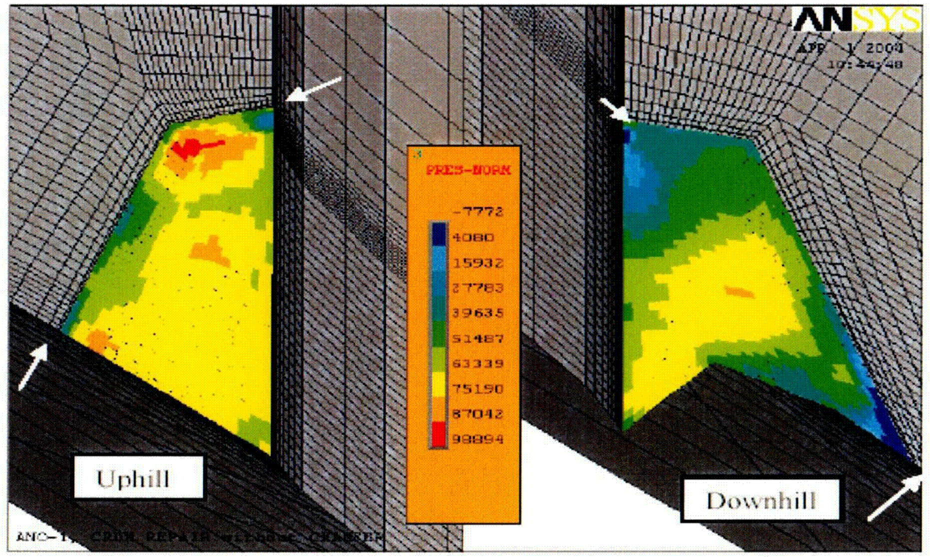




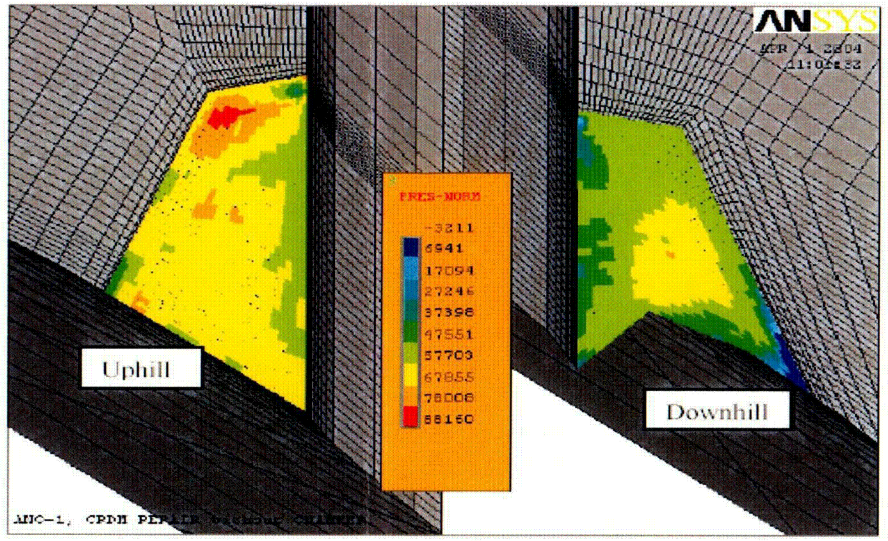


Flaw Model *Chamfer sizes marked show elements removed. Note for the downhill location, both design chamfers have the same elements removed.*	**Path selected for hoop stress** *The path begins at the J-groove weld corner and proceeds through the corner of the J-groove prep to the OD of RVH*	**Residual Stress Only -Hoop Stress Plots** *Uphill has a higher magnitude and shows a sharper decay in the RVH base metal.* ***A highly localized stress distribution (J-groove weld and immediate vicinity) is observed.***	**Steady State Condition – Hoop Stress Plots** *Uphill has a higher magnitude and shows some reduction of peak in the weld. The decay is sharper in the uphill as in the case for the residual stress only plots.* ***A highly localized stress distribution (J-groove weld and immediate vicinity) is observed.***

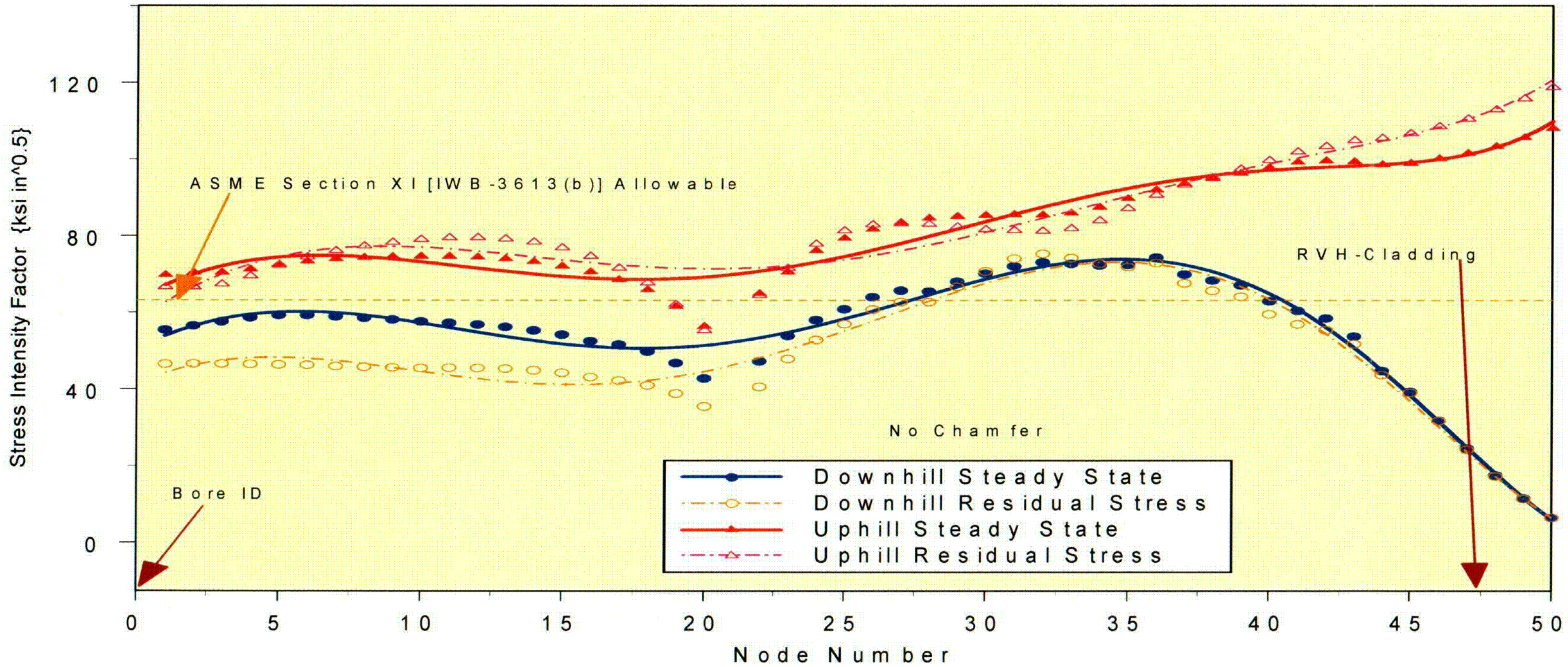
C04



a) Residual Stress Loading Only



b) Steady State Loading



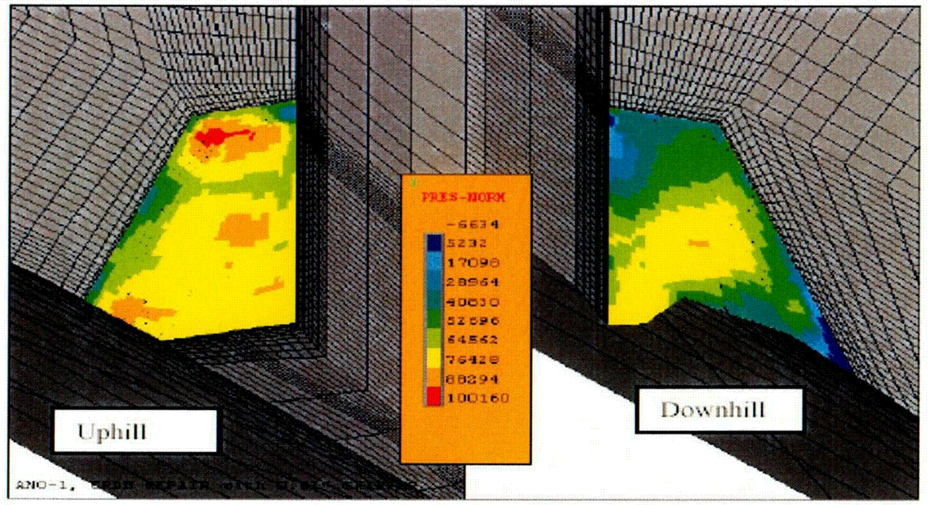
Stress Intensity Factor distribution along crack front. {Residual stress only – Open symbol; Steady state condition – Closed symbol}

Observations

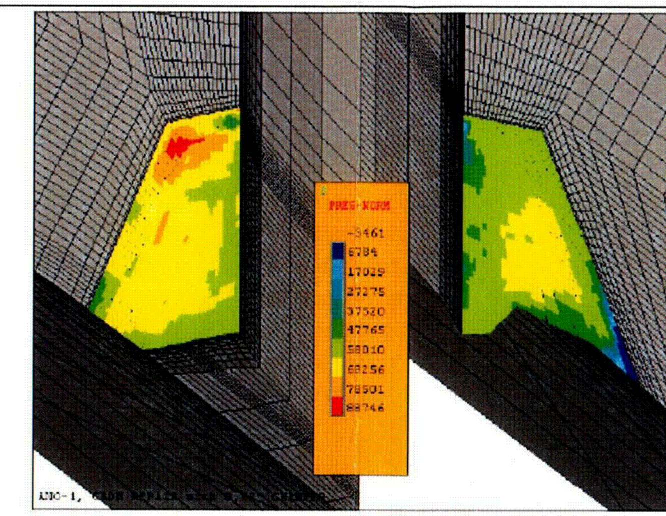
- **Steady state condition tends to make the hoop stress distribution more uniform.**
- **The stress distribution in the crack is very similar between residual stress only and steady state condition. Indicates residual stress distribution is the major contributor.**
- **The stress intensity factor distribution shows that the ASME Section XI allowable of 63.2 ksi√in. for normal operation is exceeded.**
- **The stress intensity factor for the residual stress only distribution is not significantly lower than that for the steady state condition. Demonstrates that the major contribution to the stress intensity factor is from the residual stress distribution.**
- **The low stress intensity factor (dip in the data around node 20) is located where the crack front changes direction.**
- **The sixth order polynomial fit provides a reasonable representation of the stress intensity factor distribution along the crack front. Also smoothes out the sharp drop in the stress intensity factor around node 20.**

C05

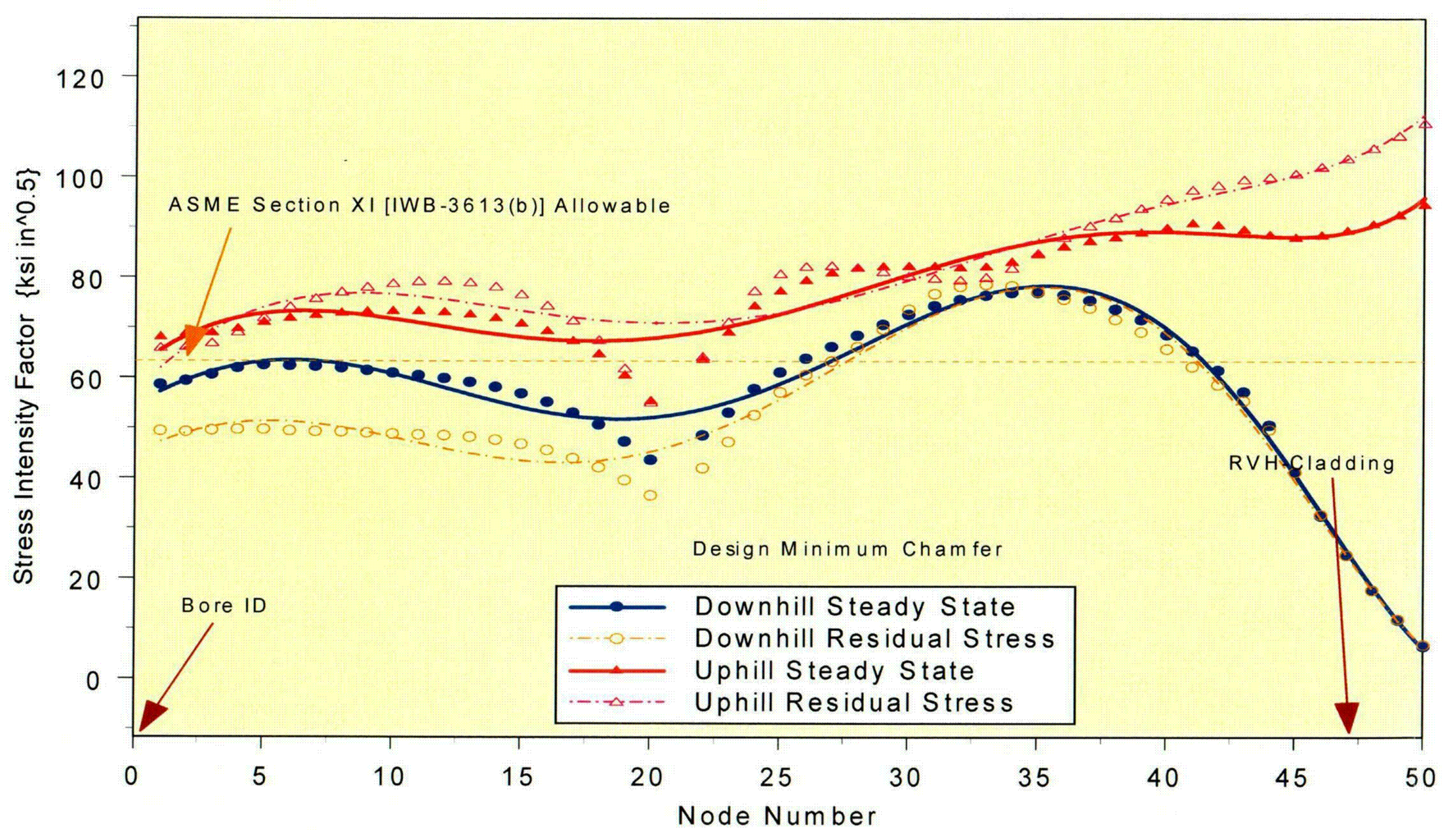
Fracture Mechanics Results for Design Minimum Chamfer Case



a) residual Stress Loading Only



b) Steady State Loading



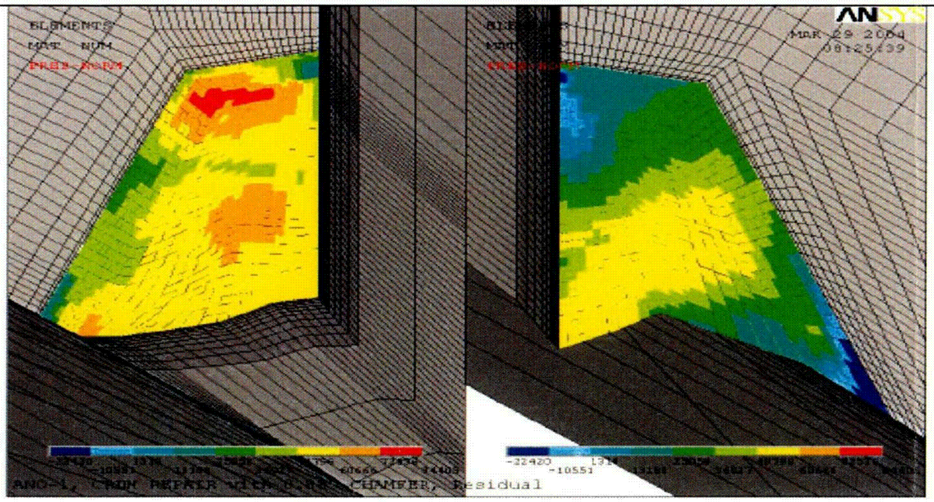
Stress Intensity Factor distribution along crack front. {Residual stress only – Open symbol; Steady state condition – Closed symbol}

Observations

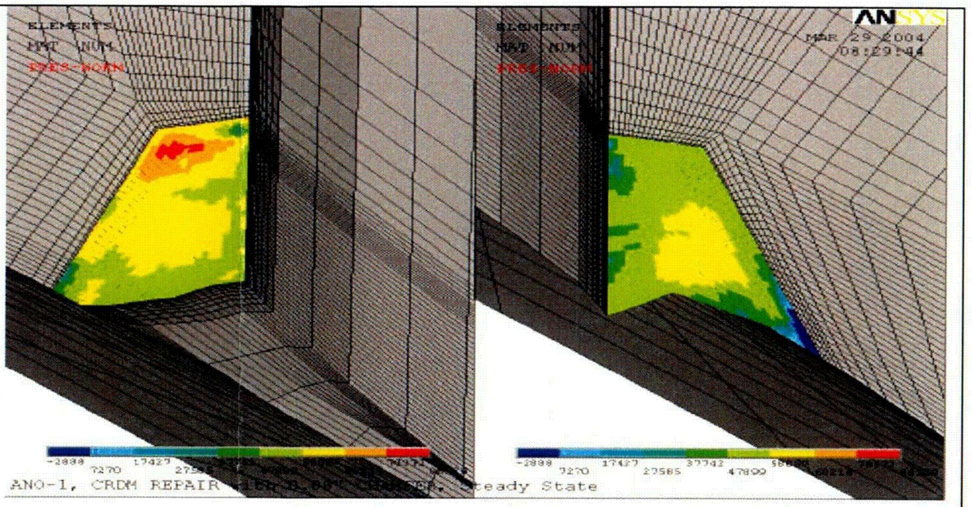
- **Steady state condition tends to make the hoop stress distribution more uniform.**
- **The stress distribution in the crack is very similar between residual stress only and steady state condition. Indicates residual stress distribution is the major contributor.**
- **The stress intensity factor distribution shows that the ASME Section XI allowable of 63.2 ksi√in. for normal operation is exceeded.**
- **The stress intensity factor for the residual stress only distribution is not significantly lower than that for the steady state condition. Demonstrates that the major contribution to the stress intensity factor is from the residual stress distribution.**
- **The low stress intensity factor (dip in the data around node 20) is located where the crack front changes direction.**
- **The sixth order polynomial fit provides a reasonable representation of the stress intensity factor distribution along the crack front. Also smoothes out the sharp drop in the stress intensity factor around node 20.**

C06

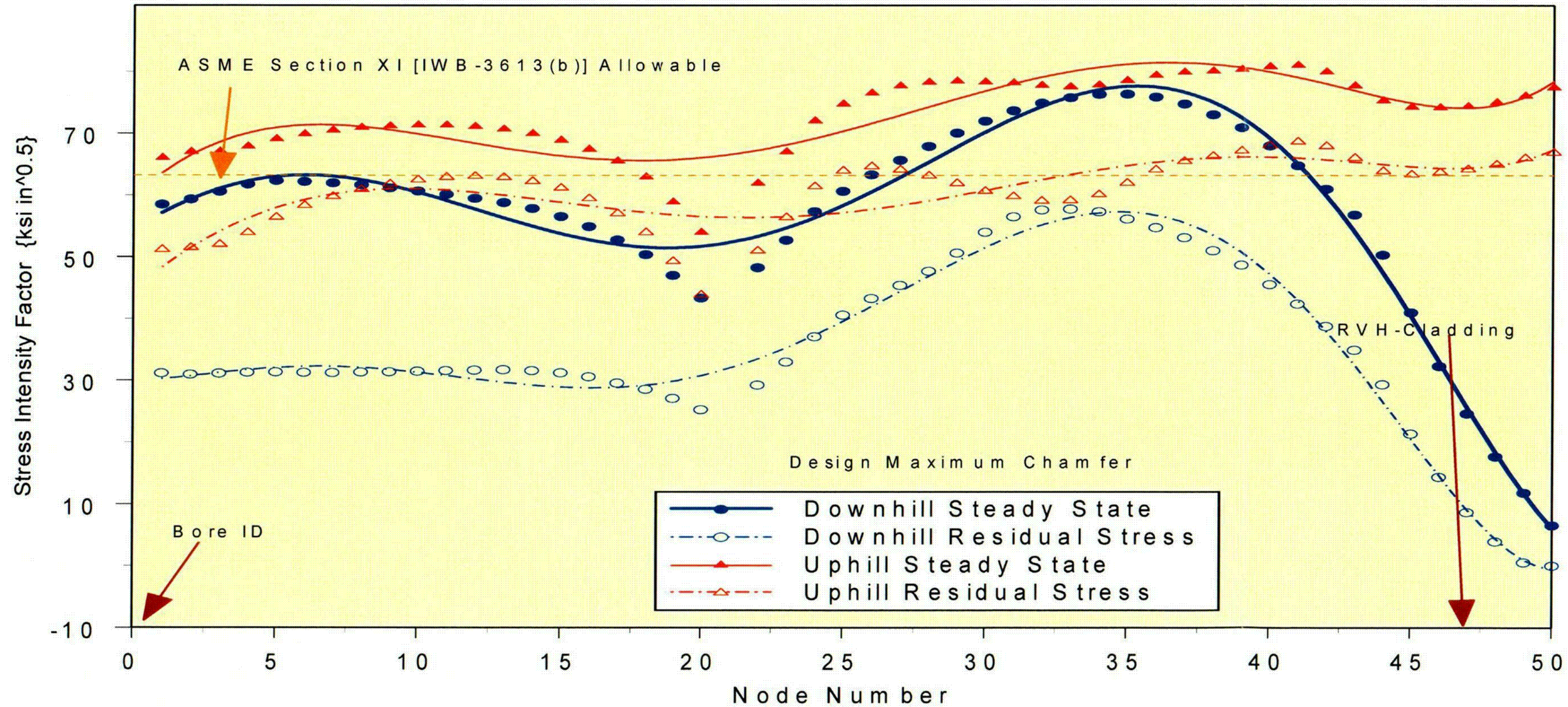
Fracture Mechanics Results for Design Maximum Chamfer Case



a) Residual Stress Loading Only



b) Steady State Loading



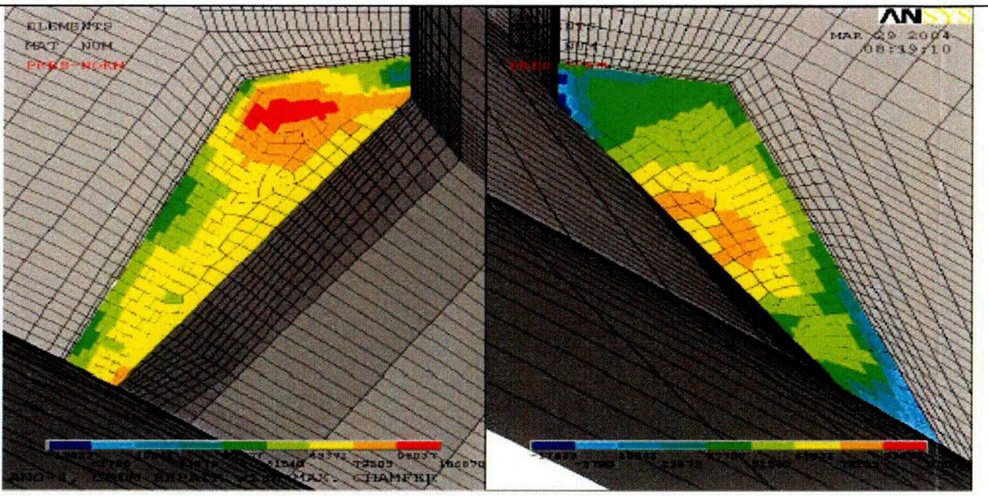
Stress Intensity Factor distribution along crack front. {Residual stress only – Open symbol; Steady state condition – Closed symbol}

Observations

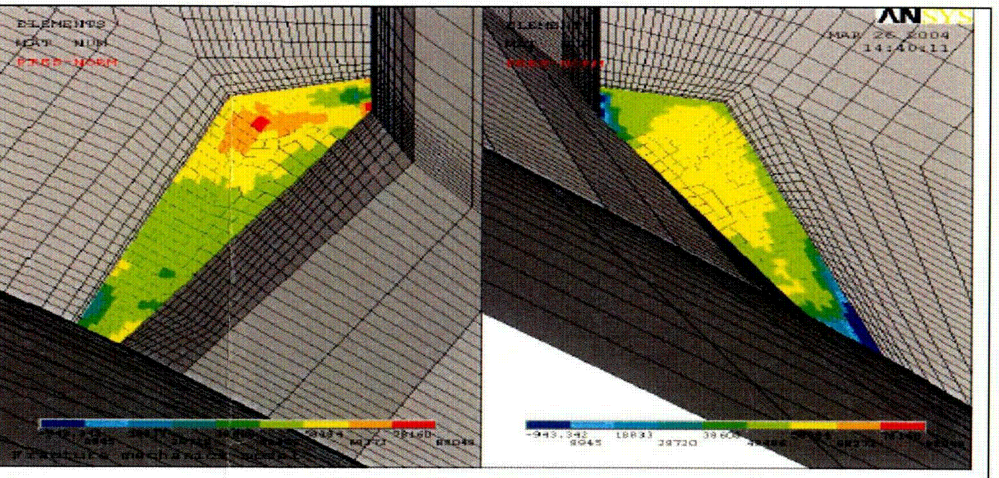
- Steady state condition tends to make the hoop stress distribution more uniform.
- The stress distribution in the crack is very similar between residual stress only and steady state condition. Indicates residual stress distribution is the major contributor.
- The stress intensity factor distribution shows that the ASME Section XI allowable of 63.2 ksi√in. for normal operation is exceeded.
- The stress intensity factor for the residual stress only distribution is not significantly lower than that for the steady state condition. Demonstrates that the major contribution to the stress intensity factor is from the residual stress distribution.
- The low stress intensity factor (dip in the data around node 20) is located where the crack front changes direction.
- The sixth order polynomial fit provides a reasonable representation of the stress intensity factor distribution along the crack front. Also smoothes out the sharp drop in the stress intensity factor around node 20.

C07

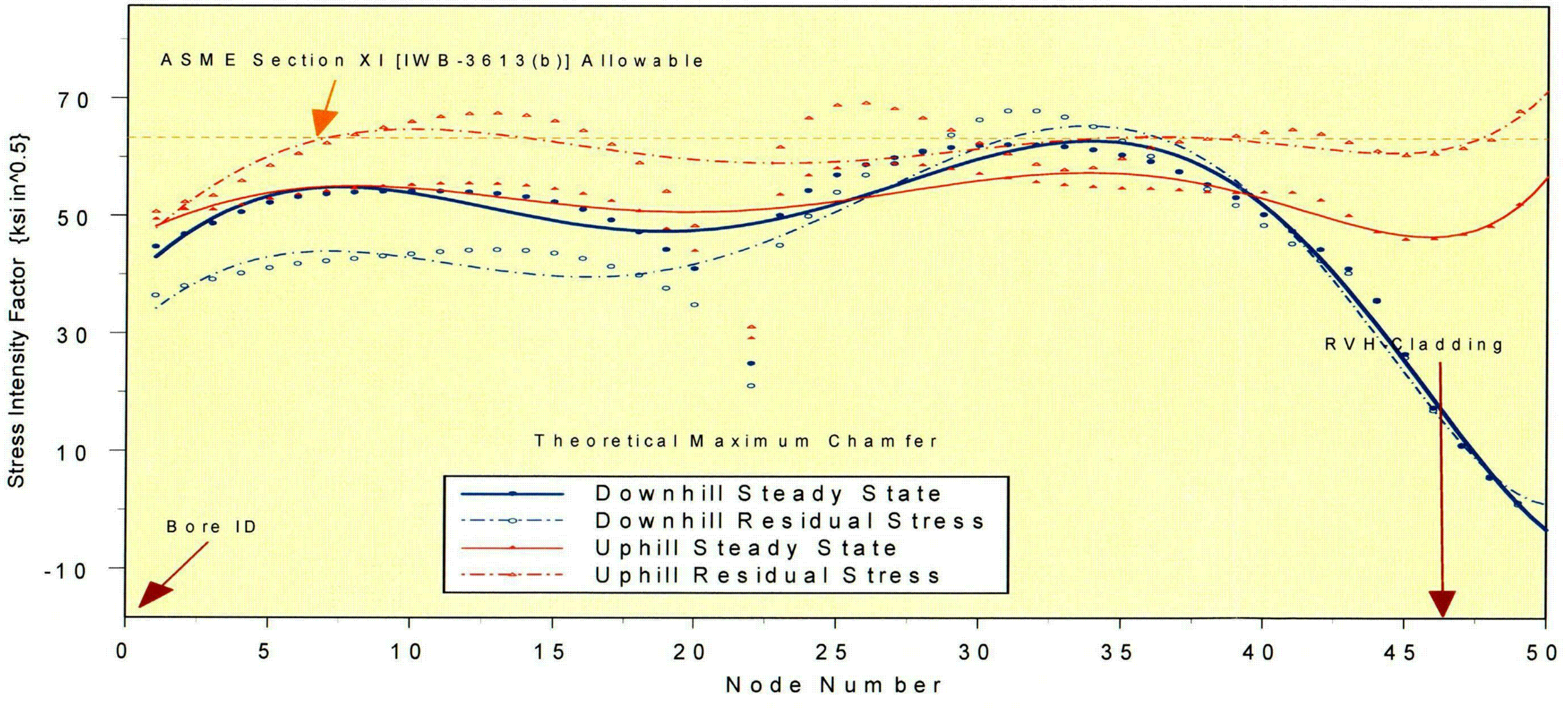
Fracture Mechanics Results for Theoretical Maximum Chamfer Case



a) Residual Stress Loading Only



b) Steady State Loading



Stress Intensity Factor distribution along crack front. {Residual stress only – Open symbol; Steady state condition – Closed symbol}

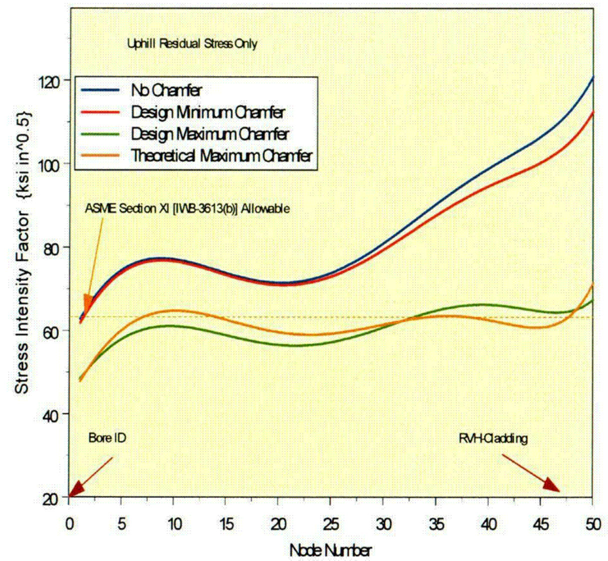
Observations

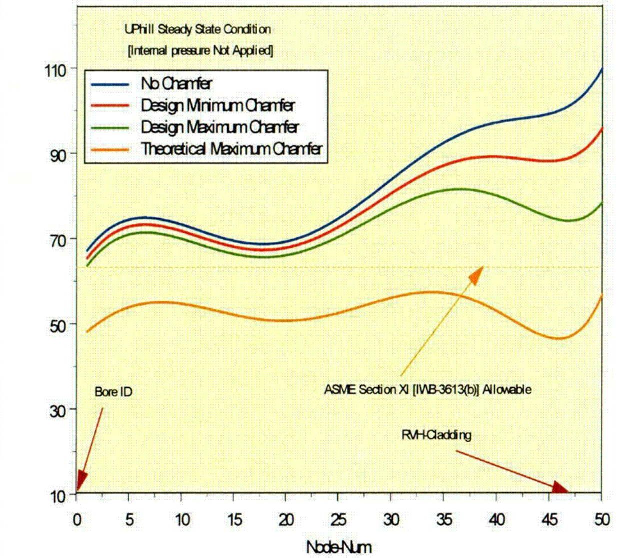
- **Steady state condition tends to make the hoop stress distribution more uniform.**
- **The stress distribution in the crack is very similar between residual stress only and steady state condition. Indicates residual stress distribution is the major contributor.**
- **The stress intensity factor distribution shows that the ASME Section XI allowable of 63.2 ksi√in. for normal operation is exceeded at some isolated locations.**
- **The stress intensity factor for the residual stress only distribution is somewhat lower than that for the steady state condition. Demonstrates that residual stress distribution contribution remains significant.**
- **The low stress intensity factor (dip in the data around node 20) is located where the crack front changes direction.**
- **The sixth order polynomial fit provides a reasonable representation of the stress intensity factor distribution along the crack front. The drop in the stress intensity factor near node 20 is discernable. This is due to the significant reduction in the weld size by the theoretical maximum chamfer. The polynomial fit smoothes out the sharp drop in the stress intensity factor around node 20.**

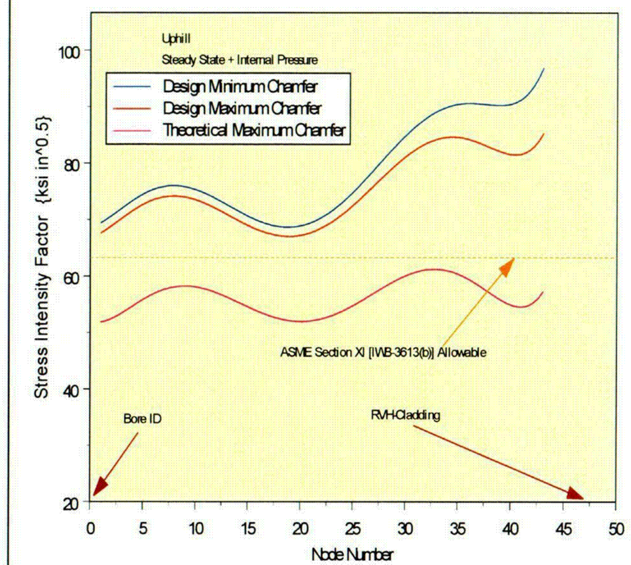
C08

Comparison of all Fracture Mechanics Results

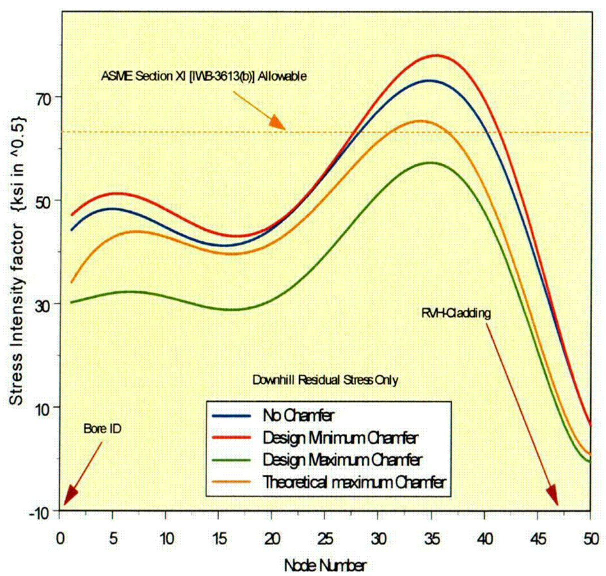
UPHILL

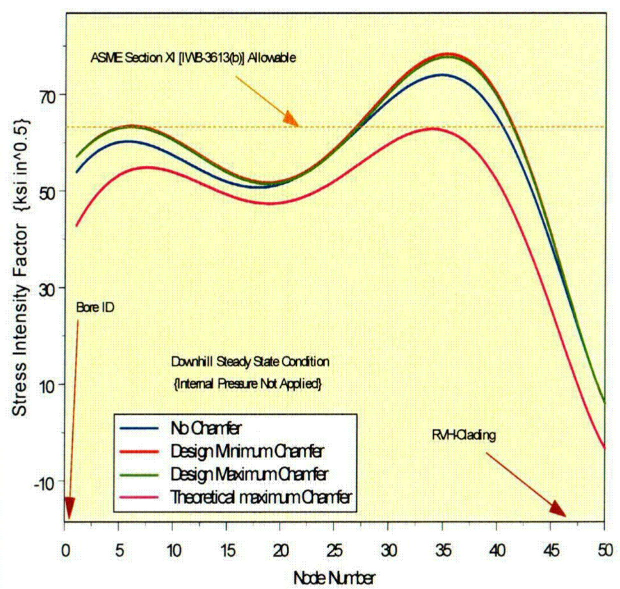


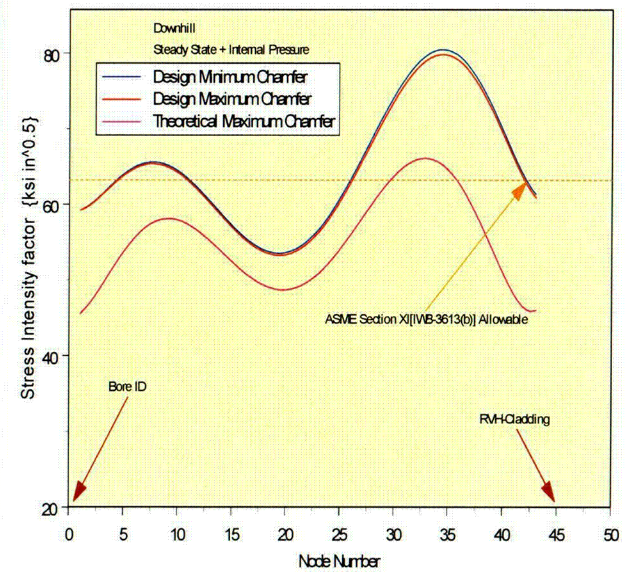




DOWNHILL







Residual Stress Only	Steady State Condition	Steady State + Internal Pressure on Crack Face

Observations

- The ASME Section XI allowable is not met.
- Theoretical maximum chamfer does not sufficiently reduce the stress intensity factor below the ASME Section XI allowable. In addition, the feasibility for installing a theoretical maximum chamfer in the field is remote.
- A difference between the design minimum and design maximum chamfer is small.
- Analysis demonstrates that the residual stress distribution has a major contribution to the stress intensity factor along the crack front.
- This analysis considering the prevailing residual, operating stress distribution and the internal pressure on the crack face shows that the ASME Section XI allowable cannot be met.

C09

Technical Basis for Entergy Method of Analysis

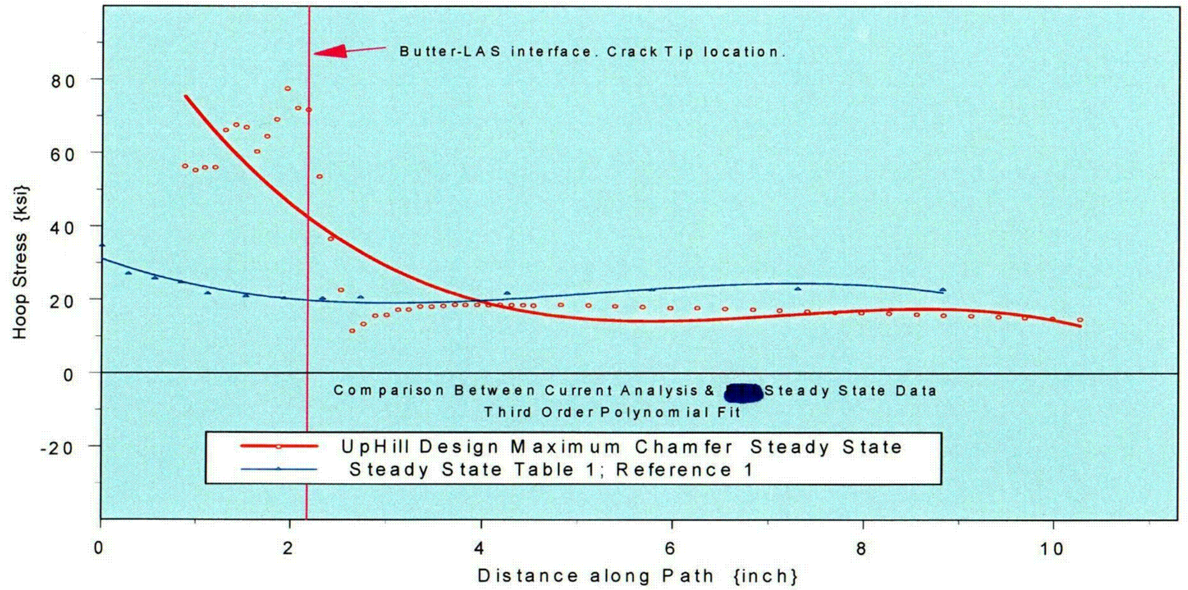
Fracture Mechanics Model

Closed Form Solution vs. Finite Element Method:

Closed form solutions limited to Weight Function Method or Remote Stress Method.

Weight Function Method (one model; authenticity unverified) requires the stress distribution to be defined by a third order polynomial. The third order polynomial does not represent the highly localized stress distribution (accounting for residual stresses) accurately (see figure below). Drawbacks of such a model are:

1) **Need for several paths to be considered to obtain the maximum stress distribution.**
2) **The poor fit for the highly localized stress distribution will lead to significant error in the estimation of the stress intensity factor along the crack front.**



Remote Stress Method (one model by Raju-Newman for corner cracks at a bore hole in flat plates remotely loaded in tension and bending NASA TM-85793) has the following drawbacks:

1) **Requires the decomposition of the highly localized stress field into Membrane and Bending stress components that are applied at the remote boundaries. Will not capture the local effects at the crack tip since the model was developed for general loading.**
2) **The model geometry is for a flat plate with a symmetrical bore. Application of interest is a non-radial bore in a curved reactor vessel head.**

The Finite Element Method models the geometry exactly and the stresses can be applied directly. No simplifying assumptions are needed. This method also captures the significant constraint that exists at the crack tip, which is created by the residual stress distribution. Hence, Entergy selected the finite element method to obtain an accurate estimate of the stress intensity factor distribution along the crack front.

Consideration of Residual Stress

- **Entergy analysis has demonstrated that residual stress is a significant contributor to the prevailing stress intensity factor at the crack tips.**
- **Analytical and experimental studies described in the literature have demonstrated that:**

1) **Residual stresses caused by welding create a severe constraint at the crack tip. The constraint was found to increase the propensity for brittle fracture that is not discernable by analysis which considers applied loads alone.**
2) **The residual stresses increase the crack driving force at the crack tip.**
3) **Ignoring the residual stress in the analysis tends to significantly over predict the failure load.**

- **The residual stress has a significant influence at the crack front, which is located at the fusion line (interface) between the Inconel Alloy 600 weld metal and the low alloy carbon steel reactor vessel head.**
- **Therefore, Entergy concluded that the residual stress distribution must be considered in the determination of the prevailing stress intensity factor.**

The results from analysis performed by Entergy for ANO-1 J-groove weld remnant flaw are summarized in Table 1.

Table 1 : Maximum SIF from Fracture Mechanics Analysis

J-groove Weld Remnant Configuration	Maximum Applied Stress Intensity Factor[1] (ksi√in)		
	Steady State Operation[2]	Residual Stresses Only[3]	Operating Condition Only[4]
No Chamfer	77.4 – Downhill 103.4 - Uphill	75.3 – Downhill 105.0 – Uphill	2.1-Downhill Note 5 – Uphill
Design Minimum Chamfer	80.0 –Downhill 94.4 - Uphill	78.6 – Downhill 99.3 – Uphill	1.4 – Downhill Note 5 – Uphill
Design Maximum Chamfer	79.4 – Downhill 84.8 - Uphill	57.8 – Downhill 68.7 – Uphill	21.6 – Downhill 16.1 Uphill
Theoritical Maximum Chamfer	65.2 – Downhill 62.5 - Uphill	67.9 – Downhill 69.1 – Uphill	Note 5 –Downhill Note 5 - Uphill

Notes:

1) *The applied SIF is based on considering the three conditions provided in 2, 3, and 4 below.*
2) *The steady state condition is the combined SIF based on residual stress plus the steady state operating stresses (pressure and temperature).*
3) *The residual stress condition is based on the residual stress state after completion of the specific operation on the J-groove weld as indicated by the configuration column.*
4) *The operating condition is the difference between the steady state condition and the residual stress state. This column provides the SIF estimate due to the operating condition alone.*
5) *The SIF due to the residual stress is higher than at steady state operating condition.*

C10

ASME Code Considerations

ASME Section XI {IWB-3613(b)}	ASME Section III	ASME Section XI "Appendix G"
Basis for safety factor of √10. **1) Maintain design margin of Section III** **2) The stress intensity factor has a square root relationship with flaw size as: $K_I = \sigma\sqrt{(\pi a)}$; results in a flaw size safety factor of 9.** **3) The flaw size safety factor rounded upwards to 10.** **4) Resulted in a √10 (3.16) safety factor on stress intensity factor.** **5) The design safety factor of 3 (Section III) was based on limiting allowable general membrane stress to one-third of the material ultimate tensile strength (UTS) such that gross deformation of the pressure vessel was avoided.**	**Consideration of local stresses is differentiated. The differentiation is as follows:** **1) The primary bending stress (P_b) and local primary membrane stress (P_L) are to be lower than 1.5 x S_m or material yield strength.** **2) The stress range when considering secondary stresses is increased by an additional factor of "2" to 3.0 x S_m. This results in a nominal safety factor of 2 for local primary stress with consideration of bending and local stress effects. This limit was imposed to prevent gross deformation due to secondary membrane stresses.**	**Recognizes different safety factors based on loading type (general membrane and local stresses). The governing equation provided in Paragraph G-2222 is:** $K_{Ia} \geq 2(K_{Im} + K_{Ib})_{Primary} + (K_{Im} + K_{Ib})_{Secondary}$ **This shows that the safety factor for primary stresses is 2 and that for secondary stresses is 1.**

Summary of Code Analysis

- **The safety factor consideration in Section III and Appendix G to Section XI are based on through-wall stress distribution, which is also the consideration for the safety factor in IWB-3600 of Section XI.**
- **However in IWB-3613(b) the safety factor applies to all stresses regardless of their distributional component (general vs. local). Results in a conservatively low allowable stress intensity factor when the primary contribution to the stress intensity factor is from a highly localized stress distribution.**
- **A reasonable approach, considering the differentiation present in Section III and Appendix "G" to Section XI, can be defined as:**

$$K_{Ia} \geq 3(K_{Im} + K_{Ib})_{Primary} + 1.5(K_{Im} + K_{Ib})_{Secondary\ or\ Residual}$$

- **When it is demonstrated that the predominant loading is due to a highly localized residual stress distribution, an alternate method to deduce the safety factor is proposed as follows:**
  1) **The structure of the safety factor for primary bending and primary local primary membrane is 2/3 of that for the general primary membrane stress. Therefore, this would reduce the safety factor to 2 for the highly localized stress distribution.**
  2) **Thus; the allowable stress intensity factor for a highly localized stress distribution would be: $K_{ITotal} \leq K_{Ia}/2$**

A worked example using the stress intensity factor values from Table 1 for the Design Minimum Chamfer case, shows the following :

Criteria 1: $K_{Ia} \geq 3.0(K_{Im} + K_{Ib})_{Primary} + 1.5(K_{Im} + K_{Ib})_{Secondary\ or\ Residual}$

$3(16.1)_{Operating\ Condition} + 1.5(68.7)_{Residual} = 151.4 \leq 200$ *Uphill Flaw*
$3(21.6)_{Operating\ Condition} + 1.5(57.8)_{Residual} = 151.5 \leq 200$ *Downhill Flaw*

Alternate Criteria $K_{ITotal} \leq K_{Ia}/2$

$2(84.8) = 169.6 \leq 200$ *Uphill Flaw*
$2(79.4) = 158.8 \leq 200$ *Downhill Flaw.*

Conclusions:

- **Significant margin against brittle fracture exists based on either of the two acceptance criteria (criteria 1 and alternate criteria) proposed.**
- **The overall approach, in the Entergy analysis presented, is conservative in that:**
  1) **The fracture mechanics evaluation has been based on a hypothetical flaw that is assumed to exist in the entire J-groove weld and butter.**
  2) **The evaluation is based on linear elastic fracture mechanics principles with an assumed fracture toughness of 200 ksi√in. At elevated temperatures, the value of the allowable fracture toughness is assumed, and the principles of elastic-plastic fracture mechanics, if used, demonstrates that significantly more margin does exist.**

EPFM Analysis in Support of Entergy Relief Request ANO-1-R&R-006

Structural Integrity Associates, Inc.

Overview

- ASME Section XI Flaw Evaluation rules for Vessels are based on LEFM (Paragraph IWB-3610 and Appendix A)
- These require safety factor (SF) of ~3 for normal operating loads, including:
  - **Primary Stresses (i.e., pressure plus mechanical loads)**
  - **Secondary and Peak Stresses (i.e., thermal, residual and highly localized stresses)**
- Using the same safety factor for all loads is appropriate only for very brittle materials, such as:
  - **Glass**
  - **RPV beltline after irradiation embrittlement**
  - **Thick, ferritic materials at very low temperatures**

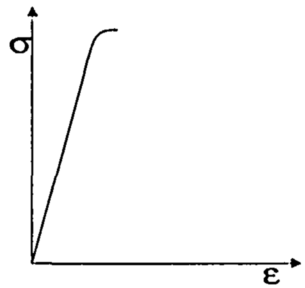
Overview (Cont'd)

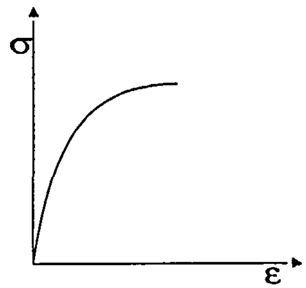
- EPFM is the more appropriate technology for non-beltline RPV materials at higher temperatures (such as the ANO-1 top head remnant cracking concern).
- Ample precedent exists in ASME Section XI for the use of EPFM and for appropriate treatment of Safety Factors
  - **Appendix C for Flaws in Austenitic Piping**
  - **Appendix H for Flaws in Ferritic Piping**
  - **Appendix K for Assessment of RPVs with Low Upper Shelf Toughness**

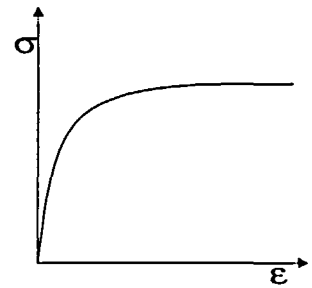
Regimes of Fracture Mechanics

Fracture Mechanics

Linear Elastic Fracture Mechanics (LEFM)	Elastic-Plastic Fracture Mechanics (EPFM)	Limit Load (Net Section Plastic Collapse)







Linear Elastic Fracture Mechanics (LEFM)

- Brittle Materials
- High Strength / Low Toughness
- Ferritic Steels at Low Temperature

Elastic-Plastic Fracture Mechanics (EPFM)

- Semi-Ductile Materials
- Moderate Toughness
- Ferritic Steels at High Temperature
- Stainless Steels and Weldments (SAW and SMAW)

Limit Load (Net Section Plastic Collapse)

- Very Ductile Materials
- High Toughness
- Stainless Steel Base Metal and GTAW Weldments

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Safety Factor Treatment for Flaws in Austenitic Piping (Appendix C)

- **For wrought materials, cast stainless steels, GTAW and GMAW welds (i.e., extremely high ductility):**
  - Limit Load criteria applied
  - Only Primary Stresses addressed w/ SF = 2.77
  - Secondary and Peak Stresses not required to be considered
- **For SMAW and SAW welds (i.e., moderate ductility)**
  - EPFM-based criteria applied
  - Primary Stresses considered w/ SF = 2.77
  - Piping Expansion Loads (P_e) considered w/ SF= 1
  - Other forms of Secondary/Peak Stress (e.g., thermal gradients and residual stresses) not required to be considered

Safety Factor Treatment for Flaws in Ferritic Piping (Appendix H)

- **Appendix H provides screening criteria (SC) to choose appropriate analysis method:**
  - $SC \geq 1.8 \rightarrow$ LEFM
  - $1.8 > SC \geq 0.2 \rightarrow$ EPFM
  - $SC < 0.2 \rightarrow$ Limit Load
- **Safety Factor Requirements:**
  - LEFM –
    - All operating stresses considered w/ SF = 2.77
    - Residual stress considered w/ SF = 1
  - EPFM –
    - Primary Stresses considered w/ SF = 2.77
    - Piping Expansion Loads (Pe) considered with SF= 1
    - Other forms of Secondary/Peak Stress (e.g., thermal gradients and residual stresses) not required to be considered
  - Limit Load –
    - Only Primary Stresses addressed w/ SF = 2.77
    - Secondary and Peak Stresses not required to be considered
- **ANO-1 Top Head clearly in EPFM regime (SC ~ 0.38)**

Safety Factor Treatment for RPVs with Low Upper Shelf Toughness (Appendix K)

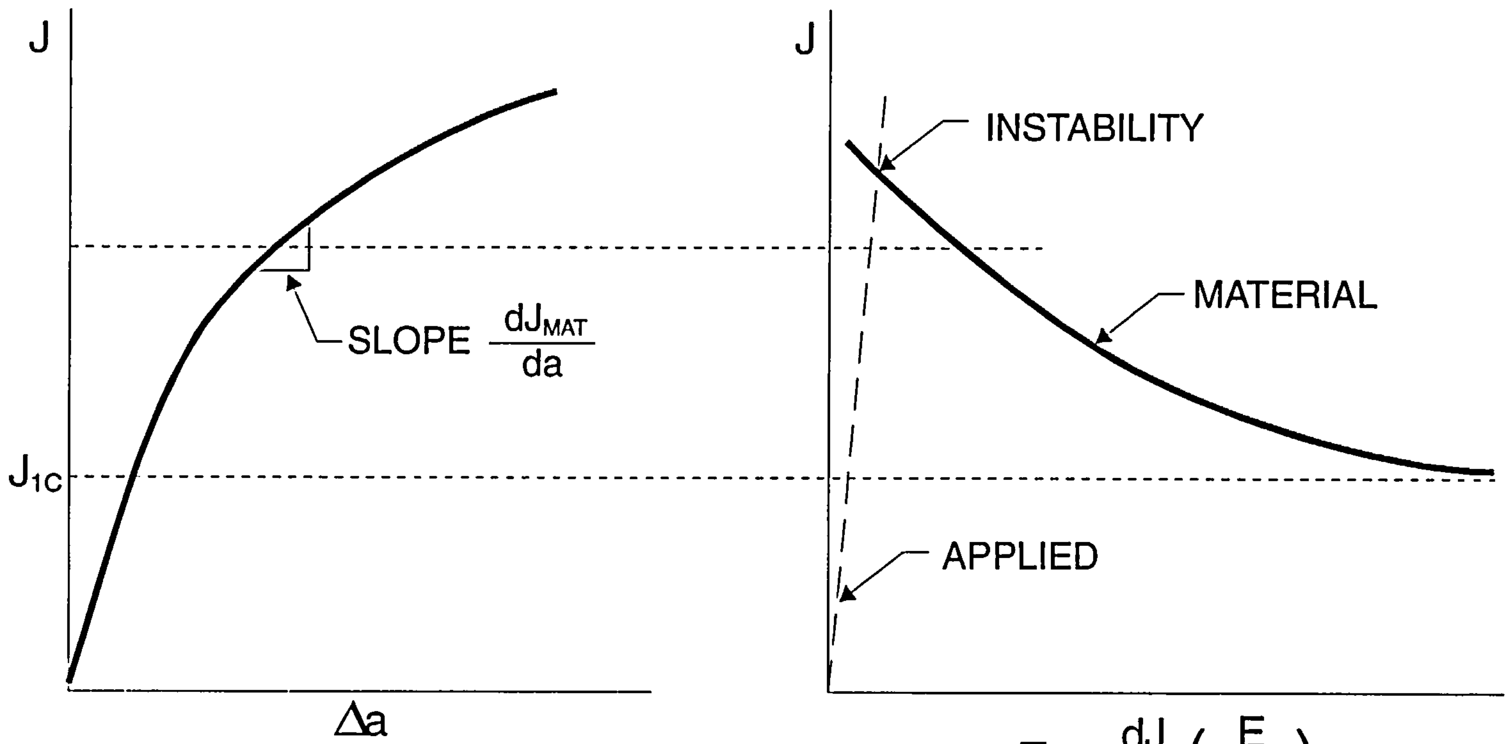
- **EPFM-based criteria applied**
  - ♦ Primary Stresses considered w/ SF = 1.25
  - ♦ Thermal Stresses (radial gradients) considered w/ SF = 1
  - ♦ Residual Stresses not considered
- **Simplified EPFM procedure provided which permits J to be approximated from LEFM K calculations at an effective flaw depth for small scale yielding:**

$$a_e = a + [1/(6\pi)] [(K_{Ip} + K_{It})/\sigma_y]^2$$

$$J = (K'_{Ip} + K'_{It})^2/E'$$

- **Small safety factor of 1.25 attributed to evaluation of "hypothetical flaw", not a flaw detected by NDE (as in Appendices C and H)**
- **Appendix K procedure applied to ANO-1 top head with two treatments of safety factors:**
  - ♦ SF = 3 on operating loads; SF = 1.5 on residual stresses
  - ♦ SF= 3 on all loads

EPFM Tearing Instability Concept



$$T = \frac{dJ}{da}\left(\frac{E}{\sigma_{ys}^2}\right)$$

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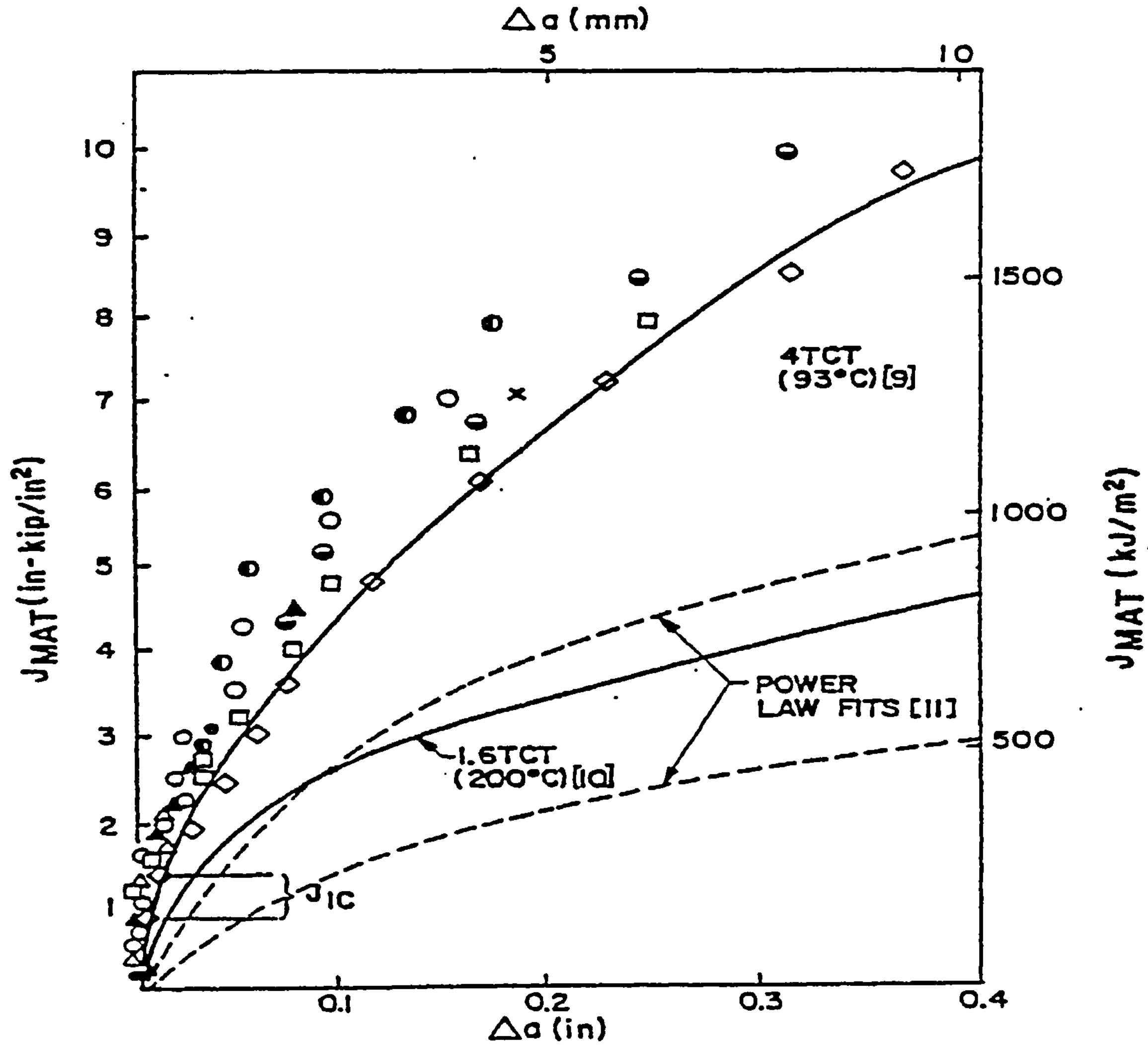
J-R Curves for Typical RPV Materials



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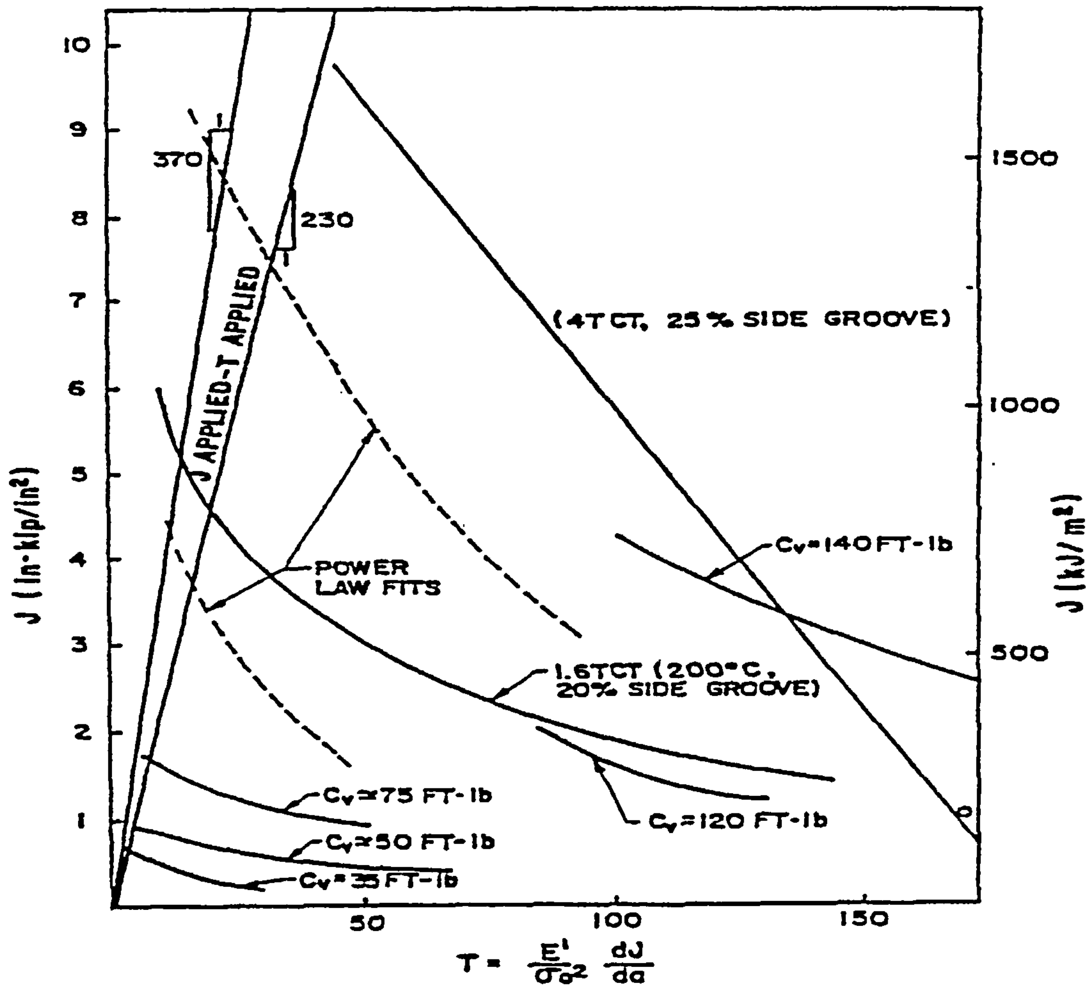
Resulting J-T Curves for Typical RPV Materials



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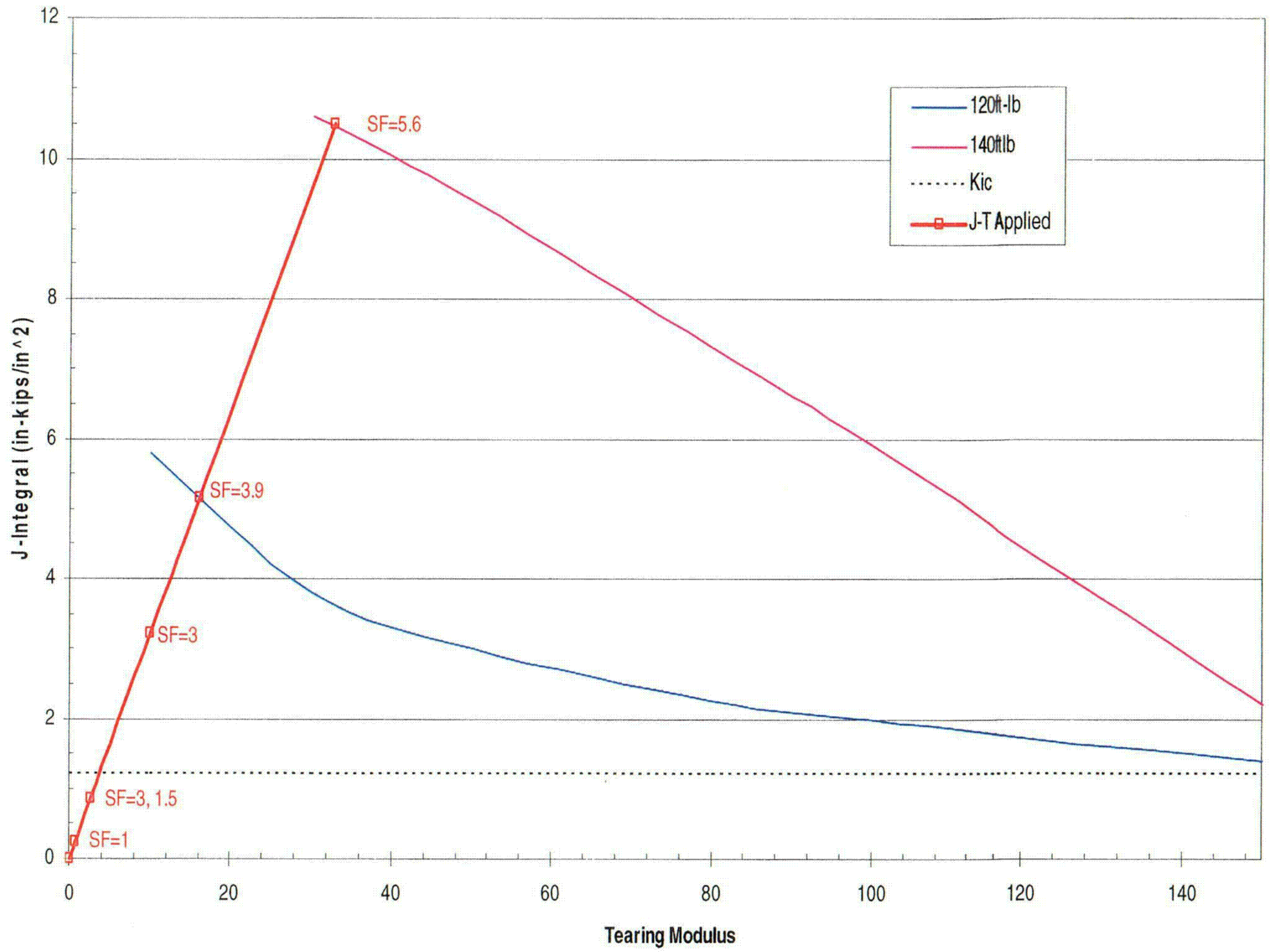
EPFM Analysis Details

	KIp	KIt	Ktotal	rp	ae
		ksi-in^1/2			inches
SF=1	16.1	68.7	84.8	0.106	1.606
SF=3, 1.5	48.3	103.1	151.4	0.338	1.838
SF=3	48.3	206.1	254.4	0.954	2.454
SF=3.89	62.6	267.2	329.6	1.601	3.101
SF=5.55	89.4	381.3	470.6	3.264	4.764

	KIp	KIt	Ktotal	K'total	J'total	T'
		ksi-in^1/2			in-kip/in^2	
SF=1	16.1	68.7	84.8	87.7	0.234	0.728
SF=3, 1.5	48.3	103.1	151.4	167.6	0.852	2.655
SF=3	48.3	206.1	254.4	325.4	3.211	10.011
SF=3.89	62.6	267.2	329.9	412.0	5.150	16.054
SF=5.55	89.4	381.3	470.6	588.3	10.500	32.731

Results of ANO-1 Top Head CRDM Nozzle EPFM Analysis



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Conclusions

- **Appropriate analysis technique for ANO-1 top head repair remnant analysis is EPFM**
  - Controlling condition is at upper shelf temperature
  - Significant ductility present
- **Ample precedent in ASME Section XI for use of EFPM and appropriate treatment of Safety Factors**
  - Clearly supports Entergy approach of using different SFs for operating versus residual stresses
  - Appendix K provides simplified EPFM technique for small scale yielding
- **Applying Appendix K technique to ANO-1 top head repair with typical RPV upper shelf material properties demonstrates that:**
  - Potential remnant crack is acceptable by a large margin with dual safety factors proposed by Entergy (3 on operating stresses, 1.5 on residual stresses)
  - Even if SF=3 applied to all stresses in EPFM analysis, results are still acceptable