From: CLARK, ROBERT W
To: Kalyanam, Kaly
Subject: WCAP-17128-NP
Date: Thursday, November 01, 2012 4:36:42 PM

Kaly,

I sent an electronic copy of the subject report to you and Jay Wallace on July 19, 2012. The subject report was too large to send in one email so I had to break it up into six pieces. I sent three emails to you that transmitted two pieces each of the report. Therefore if you combine the three emails you should have the complete WCAP report.

If you have any questions concerning this message, please let me know.

Thank you

Bob

WCAP-17128-NP
Revision 1

May 2010

Flaw Evaluation of CE Design RCP Suction and Discharge Nozzle Dissimilar Metal Welds, Phase III Study

Westinghouse

WCAP-17128-NP
Revision 1

Flaw Evaluation of CE Design RCP Suction and Discharge Nozzle Dissimilar Metal Welds, Phase III Study

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This work was performed under PWROG Project Number PA-MSC-0525.

*Electronically approved records are authenticated in the electronic document management system.
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REVISION 1

Revision 1 of this report was prepared to update the residual stresses used for the flaw tolerance evaluation of Section 6 of this report. The revised residual stresses are discussed in Section 3.2.

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Duke Energy	Catawba 1 & 2; McGuire 1 & 2 (W); Oconee 1, 2, & 3 (B&W)		X
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Florida Power & Light Group	Turkey Point 3 & 4; Seabrook (W)		X
Florida Power & Light Group	Point Beach 1 & 2 (W)		X
Luminant Power	Comanche Peak 1 & 2 (W)		X
Xcel Energy	Prairie Island 1 & 2 (W)		X
Omaha Public Power District	Fort Calhoun (CE)		X
Pacific Gas & Electric	Diablo Canyon 1 & 2 (W)		X
Progress Energy	Robinson 2; Shearon Harris (W); Crystal River 3 (B&W)		X
PSEG – Nuclear	Salem 1 & 2 (W)		X
Southern California Edison	SONGS 2 & 3 (CE)	X	
South Carolina Electric & Gas	V.C. Summer (W)		X

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Southern Nuclear Operating Co.	Farley 1 & 2; Vogtle 1 & 2 (W)		X
Tennessee Valley Authority	Sequoyah 1 & 2; Watts Bar (W)		X
Wolf Creek Nuclear Operating Co.	Wolf Creek (W)		X

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Hokkaido	Tomari 1 & 2 (MHI)		X
Japan Atomic Power Company	Tsuruga 2 (MHI)		X
Kansai Electric Co., LTD	Mihama 1, 2, & 3; Ohi 1, 2, 3, & 4; Takahama 1, 2, 3, & 4 (W & MHI)		X
Korea Hydro & Nuclear Power Corp.	Kori 1, 2, 3, & 4; Yonggwang 1 & 2 (W)		X
Korea Hydro & Nuclear Power Corp.	Yonggwang 3, 4, 5, & 6; Ulchin 3, 4, 5, & 6 (CE)		X
Kyushu	Genkai 1, 2, 3, & 4; Sendai 1 & 2 (MHI)		X
Nuklearna Elecktrarna Krško	Krško (W)		X
Nordostschweizerische Kraftwerke AG (NOK)	Beznau 1 & 2 (W)		X
Ringhals AB	Ringhals 2, 3, & 4 (W)		X
Spanish Utilities	Asco 1 & 2; Vandellos 2; Almaraz 1 & 2 (W)		X
Taiwan Power Co.	Maanshan 1 & 2 (W)		X
Électricité de France	54 Units		X

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

All Alloy 82/182 butt welds in Combustion Engineering (CE) plants are required to be inspected by the ASME Code Section XI [1]. In addition to this requirement, all of these nozzle regions must be volumetrically inspected by December 2010, in accordance with industry report, MRP-139 [2]. These inspections are required to be carried out using the performance demonstration requirements of Section XI Appendix VIII [1], and Supplement 10 of Appendix VIII. CE plants have a number of dissimilar metal (DM) butt welds in the cold leg. In particular, the large diameter cold leg reactor coolant pump (RCP) suction and discharge nozzle Alloy 82/182 butt welds have an as-built configuration that is not conducive to meeting the 90% inspection coverage requirements of MRP-139 [2] and ASME Code Appendix VIII [1]. In addition, the cast stainless steel material at the safe-end of these nozzles is not addressed by Appendix VIII or Supplement 10, and therefore, would only allow for a one-sided examination.

The large-diameter pump nozzle dissimilar metal welds are exposed to nominal cold leg temperatures of nominally 550°F, and therefore, are less susceptible to primary water stress corrosion cracking (PWSCC) initiation than nozzles in the hot leg. PWSCC initiations, as well as the rate of cracking, and overall susceptibility are a strong function of temperature. Therefore, the probability of crack initiation, as well as the crack growth rate in the cold leg, is significantly less than that of a similar crack in the hot leg.

Required inspection coverage is often difficult to obtain because of additional nozzles which penetrate the pipe and obstruct the weld region. Figure 1-1 illustrates this type of obstruction. These obstructions could also make mitigation difficult, creating the need for strong technical arguments to demonstrate the integrity of these nozzles, so realistic inspection plans can be carried out.

This document is a follow-up to the initial assessment of the flaw tolerance of these regions, using the rules of ASME Code, Section XI [1] and supersedes it for the RCP nozzle. The calculations in an earlier WCAP [22] present the maximum allowable initial flaw sizes in the DM welds, accounting for PWSCC growth, for the temperatures and loadings of interest and furthermore demonstrating the existence of a favorable flaw tolerance in these regions. This report updates those calculations by considering longer periods of operation and adding the consideration of fatigue crack growth, as well as a more detailed treatment of the residual stresses in the region.

The technical arguments documented in this report can be used for several purposes. First, they support the argument that frequent (every few outages), high-percentage (90%) coverage inspections are not necessary because crack initiation in these regions is highly unlikely. The results presented in this document support less frequent and lower-percentage coverage inspection.

Second a very large margin exists between the size flaw from which detectable leakage can be observed, and the size flaw which could cause the pipe to fail in the region of interest. This margin can be quantified in terms of relative flaw lengths of through-wall flaws or in the time required for a leaking flaw to grow to a critical flaw. This time will then be compared with the action time required for all plants detecting a leak. This action could be triggered as early as one 24 hour period, or as long as seven days, as a result of a change in the seven day moving average. This argument provides for defense in depth for this region.

This report also provides documented flaw evaluations of the regions of interest, in the case an indication is discovered during a routine ultrasonic testing (UT) examination. Specifically, the work presented herein covers the RCP suction and discharge nozzles for all CE designs with DM welds in the region, for both axial and circumferential flaw orientations. Crack growth due to both fatigue and PWSCC has been considered. These very high flaw tolerance results also support the argument that frequent, high-percentage (90%) coverage inspections are not necessary.

Figure 1-1: Example of Built-in Obstructions for an RCP Discharge Nozzle DM Weld

2 SUMMARY OF RESULTS AND CONCLUSIONS

An extensive series of evaluations have been performed on the Alloy 82/182 dissimilar metal butt welds located at the safe-end regions of the CE designed reactor coolant pump suction and discharge nozzles. These nozzles present inspection coverage challenges, which hinder the likelihood of obtaining the required inspection coverage of MRP-139 [2], and the successor document, ASME Code Case N-770 (see Appendix A). Furthermore, the geometry of the region also contributes to the difficulty of performing standard mitigation techniques.

There are two primary goals of this work:

- Provide a technical basis for revision of the inspection requirements for this region, to account for the access limitations. Specifically, changes to ASME Section XI Code Case N-770 are proposed in Section 9 of this report.
- Provide flaw evaluations which could be used to allow further operation without repair, in accordance with the rules of Section XI of the ASME code. The results of these flaw tolerance evaluations are provided in Section 6 of the report.

The first step of the project was to document the extent of the obstruction for inspection coverage. This was done by surveying the plants involved. Results showed obstructions ranged from 11% to 23% of the circumference, but by the time the work described in this WCAP was completed, progress had been made in the inspectability area, and the largest region of obstruction is now 14% of the circumference. Although the inner 33 percent of the pipe may be obstructed over this length, typically inspections do allow some limited examination of the remaining 66% of the thickness.

However, these nozzle regions operate at cold leg temperatures, nominally 550ºF and have a very high resistance to the potential for PWSCC, and a low predicted crack growth rate, if such a flaw were to exist in the region. This leads to the suggestion the required inspection regimen may be too strong for these regions, and the study described here was structured to investigate that possibility and develop a technical basis for proposing changes to inspection requirements consistent with the flaw tolerance of the region. The technical basis for these changes is described in the remainder of this report. The technical basis rests on three complementary findings:

1. The probability of a flaw existing or initiating in this region is very low;
2. There is a significant margin between the size flaw which would leak at a detectable rate, and the size flaw which would cause the pipe to fail. This provides a significant level of defense in depth for the region; and
3. The flaw tolerance of the region, for both axial and circumferential flaws, has been documented as measured by the size flaw which could grow to the ASME Code Section XI [1] allowable flaw size for either flaw type.

Probability of Cracking

A compilation of all cracking experienced in these Alloy 82/182 welds was completed, and the information used to develop a Weibull Model of cracking probability as a function of time. The full range of pump operating temperatures was considered for all affected units, and the probability of cracking was extremely low, as seen in Figure 2-1.

Defense in Depth

All CE designed plants with this pump design were surveyed, and their leakage action levels were obtained. The utilities have all committed to initiate a condition report and follow up on the source of the leak, up to and including containment entry, after identifying a leak or change in the long term trend in an unidentified leakage. Calculations of the time to grow a crack from a through-wall length resulting in the actionable leak rate of 0.1 gpm to the critical length of a through-wall flaw showed that at least 14 years are required, an extremely large margin over the one to seven day action time. These times are shown for a range of leak rates in Figure 2-2.

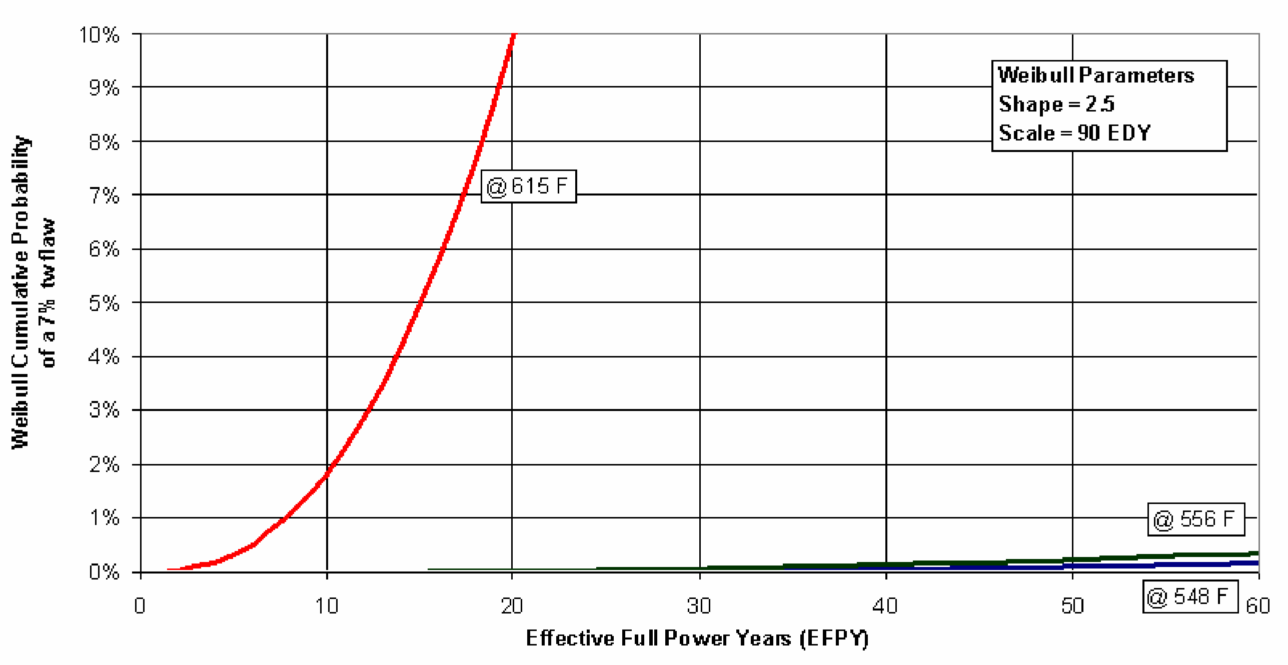

Figure 2-1: Cumulative Probability of a Flaw with a Depth of 7% of the Wall Thickness

Flaw Tolerance

A series of calculations were carried out to determine the time required for a postulated surface flaw to reach the ASME Section XI [1] allowable flaw size. Both fatigue crack growth and stress corrosion cracking were considered, and the results are presented in terms of the allowable service time for a range of flaw sizes and shapes. Results show the range of flaws which are acceptable for service periods from two to four years, for example. These results include the required Section XI [1] flaw evaluation margins and are presented for both axial and circumferentially oriented flaws. The revised design-specific residual stresses were found to be lower for circumferential flaws, and higher for axial flaws, than the stresses used in the earlier work. Circumferential flaw results are shown in Figures 6-17 through 6-20, and show that very large flaws can be tolerated in this region. Residual stress effects were found to retard flaw growth for circumferential flaws. The results for axial flaws are shown in Figures 6-13 through 6-16. While the axial flaw results are not as beneficial as the circumferential flaw results, the limited length of the flaw causes the aspect ratios to also be limited. The results for a deep axial flaw, which would have an aspect ratio a/l = 0.50, are also very acceptable, as seen in Figures 6-13 through 6-16.

The flaw tolerance work was supplemented with advanced finite element analyses, wherein the postulated flaw was allowed to grow in a natural shape, dictated by the stresses present. These results are shown in Table 2-1 and are based on a postulated surface flaw in the region which cannot be inspected, with length equal to 14% of the circumference. The depth of the flaw was varied from 20% to 30% of the wall, to bracket the range of uninspectable materials. These depths were chosen based on very conservative aspect ratios of 0.04 and 0.03, respectively. These are significantly larger than the aspect ratio of 0.1667 observed in service experience, and it is highly likely that any flaws deeper than this would have tails which would be detected in the inspected region. Results show that the postulated flaw will remain within the ASME Code [1] acceptable depth for 7.5 to over 11 years, depending on its depth, and requires between 9.3 and 13 years to reach a through-wall condition. These results do not account for the impact of the stainless steel closure weld, which induces a region of compressive stress in the mid wall region of the pipe and would further retard the crack growth.

Conclusions

This work has demonstrated that the pump safe-end to nozzle weld regions have significant margins, and therefore do not require the inspection frequency specified in [28]. The flaw tolerance option similar to that included in [28] has been used to demonstrate this within this report.

The three approaches used to support this conclusion have been consistent in their findings. There is only a very small probability of having a flaw in the cold leg region, and if it existed, the evaluations showed that more than 14 years would be required from the time a leak is discovered to the point when the integrity of the pipe would be challenged. Finally, the flaw tolerance of the weld region was examined using both classical and advanced finite element analysis techniques. It was shown that a circumferential flaw postulated in the region would require between 7.5 and 11 years to reach the ASME Code [1] limiting depth of 75% of the wall thickness. This supplementary analysis discussed in detail in Section 7 did not take advantage of the impact of the safe-end to pump closure weld, which would surely increase the times calculated.

Table 2-1: Results of Advanced Finite Element Crack Growth Analyses for Circumferential Flaws

Initial Depth/Thickness (a/t)	Initial Length/Circumference	Time to a/t = .75	Time to a/t = 1.0
0.20	0.14	10.68 years	12.52 years
0.20	0.23	9.6 years	11.1 years
0.30	0.14	7.44 years	9.34 years
0.30	0.23	6.45 years	7.85 years

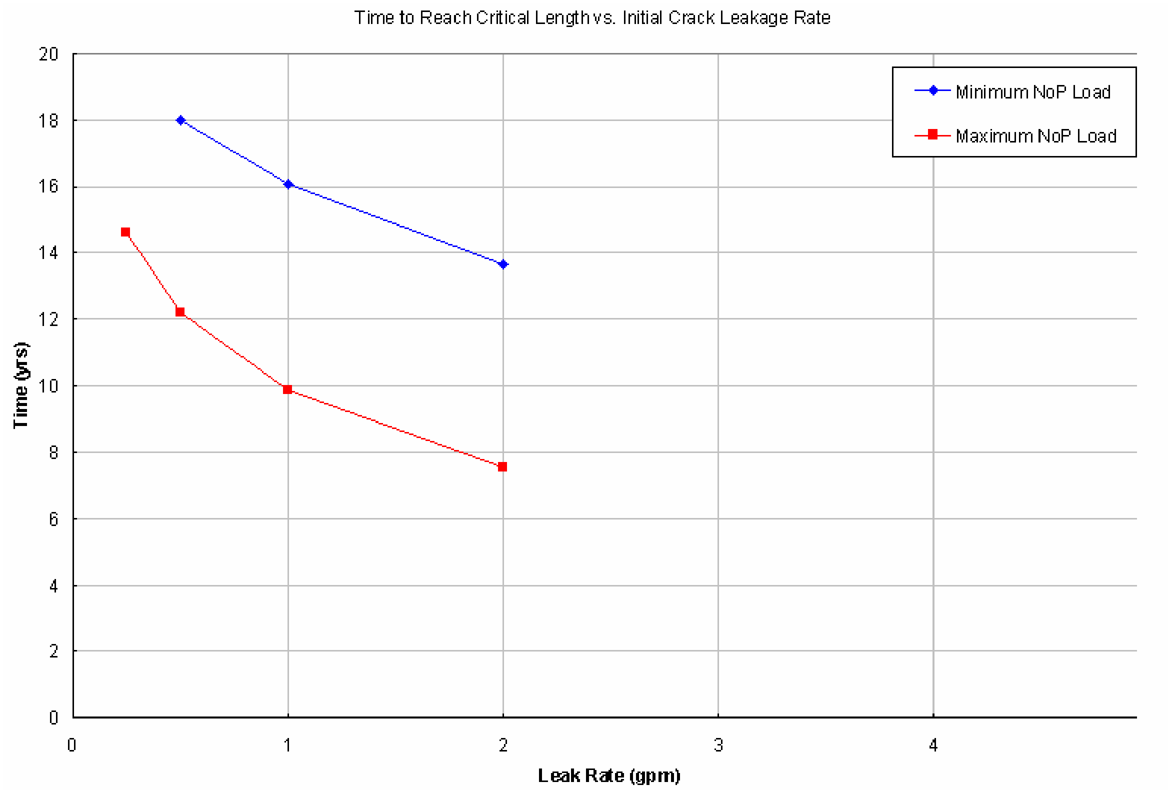

Figure 2-2: Time from Leakage to Critical Circumferential Flaw Length (No Residual Stress Case) for a Through-wall Flaw

3 SUCTION AND DISCHARGE NOZZLE LOADING AND RESIDUAL STRESSES

3.1 NOZZLE LOADINGS

The first step in the analytical evaluations reported herein is to determine the appropriate loadings for the service conditions which apply to the pump nozzle DM welds. Both the maximum allowable end-of-evaluation-period flaw sizes and stress intensity factors are functions of the piping stresses, crack geometry, and material properties. Loadings for normal, upset, and test conditions are required, as well as those for emergency and faulted conditions.

The RCP suction and discharge nozzle DM weld regions are subject to piping reaction loads resulting from pressure, thermal expansion, self-weight, seismic, and accident loading conditions. The self-weight is generally small, often not available separately, and included with normal operating conditions. Therefore, it is not included in the detailed flaw evaluations performed here. Upset, emergency, and faulted load conditions, such as operating or design basis seismic, safe shutdown seismic, loss of coolant accident (LOCA), branch line pipe break (BLPB), and accident conditions were obtained from the engineering specifications and summarized in [22] for the RCP suction and discharge nozzles. Load combinations are plant specific. For this analysis, all load conditions were classified as:

1. Normal operation (NOP) represents thermal loading;
2. Normal operation plus operating basis earthquake (NOP + OBE), representing the upset load level;
3. Normal operation plus safe shutdown earthquake (NOP + SSE), representing the emergency load level; and
4. Normal operation plus accident (NOP + SSE + LOCA, NOP + SSE + BPLB, NOP + accident), representing the faulted load level.

The normal operation loading condition pipe forces and bending moments, along with the internal pressure loads, were used for the PWSCC flaw growth estimation.

Load condition number 2, listed above, was used for the maximum allowable end-of-evaluation period flaw size for the normal and upset load conditions, as well as conditions 3 and 4 of the corresponding flaw size for the emergency and faulted load conditions. Normal operation loads (without pressure) were used as secondary thermal stresses. The internal pressure load and additional loads beyond the normal operation are assumed to be due to additional pipe mechanical loads (seismic, LOCA, BLPB, and accident) and are used for the primary membrane and bending stresses.

Piping stresses for all the plants were calculated using the corresponding RCP weld geometries are provided in [22]. The nominal dimensions used for this evaluation are shown in Table 3-1. These dimensions are designed to be best estimates for the weld region of interest here. These stresses are bounded first within each plant; then bounded again to obtain overall maximum values to be used as a generic candidate for the flaw evaluation. Nominal dimensions were then used in the actual calculation of the PWSCC crack growth, fatigue crack growth, and maximum end-of-evaluation-period flaw sizes.

Table 3-1: Nominal Dimensions Used for Flaw Evaluation

Parameter	**Suction, Discharge (in)**
Outside Diameter	36
Inside Diameter	30
Thickness	3

Operating pressure is 2,250 psi, and the temperature ranges between 543°F and 553°F. The design pressure of 2,500 psi and temperature of 553°F were used in all flaw evaluations to provide some conservatism in the evaluations. High pressure results in higher stress, and higher temperature results in higher crack growth rates.

The stresses at the DM welds for normal, upset, emergency, and faulted conditions were determined using the following equations in the evaluation:

$$\sigma_{m-tot} = \frac{F_{a-tot}}{A} \qquad \text{Equation 3-1}$$

$$\sigma_{b-tot} = \frac{M_{b-tot}}{Z} \qquad \text{Equation 3-2}$$

$$\sigma_{e} = \frac{F_{a-nop}}{A} + \frac{M_{b-nop}}{Z} \qquad \text{Equation 3-3}$$

where:

$\sigma_{m\text{-tot}}$ = primary membrane stress due to total load
$\sigma_{b\text{-tot}}$ = primary bending stress due to total load
σ_e = total secondary stress due to normal operation loads
F_{a-tot} = axial force due to pressure and mechanical loads
F_{a-nop} = axial force due to thermal loads
M_{b-tot} = bending moment across the pipe cross-section due to mechanical loads
M_{b-nop} = bending moment across the pipe cross-section due to thermal loads
A = pipe cross-sectional area
Z = pipe cross-sectional modulus

The piping loads are tabulated in [22]. For the PWSCC analysis, only the steady-state operating loads (due to pressure, self-weight, and thermal) are used. Along with the operating loads, the hoop and axial residual stress distributions discussed in Sections 3.2 and 3.3 were used to calculate both the fatigue and PWSCC crack growth. External loads, such as seismic and accident conditions and take place for only a short duration, would not have any significant impact on the overall crack growth.

3.2 RESIDUAL STRESSES

The dissimilar metal weld of interest in this report attaches the stainless steel safe-end to the carbon steel piping segment leading to the RC pump. The piping segment and nozzle are fabricated in the shop and can be seen in Figure 1-1~~Figure 1-1~~. The portion of the pipe segment where the safe-end will be attached is buttered, and then the entire segment is stress relieved. After the stress relief, the stainless steel safe-end is attached to the pipe segment with the dissimilar metal weld, and no further stress relief is applied and not required. The segment can then be welded to the pump suction or discharge nozzle in the field, with a stainless steel to stainless steel weld.

The residual stresses do not affect the allowable flaw size, as determined for these ductile materials per Appendix C of Section XI [1]; yet both the fatigue and PWSCC crack growth calculations are affected. The effect on fatigue crack growth is not large because the residual stress exists for both the maximum and minimum points of each transient. The effect on PWSCC is important because the residual stresses make up a significant portion of the total stress.

The residual stresses from the fabrication of the dissimilar metal weld were obtained from finite element modeling, and the model is shown in Figure 3-1~~Figure 3-1~~. Note that an axial flaw is more or less self limiting, by the width of the dissimilar metal weld.

The methodology used for the thermal solution is described in some detail below. The temperature constraint method was used, where the weld beads are held to a near-melt temperature, and then allowed to cool.

Each weld bead was held at temperature for 10 seconds in the thermal solution, to capture the effect of heat input on the weld simulation. This analysis was used to obtain the residual stress results for the loop piping - pump nozzle connection after assembly for four cases. The cases are as follows:

1. A 10% inner diameter weld repair with heat treatment after the loop piping butter, but with no heat treatment after the weld repair. Note that this condition is similar to the original condition of this region with no repair, as the weld is back chipped.
2. A 10% inner diameter weld repair with heat treatment after the loop piping butter and with heat treatment after the weld repair.
3. A 25% inner diameter weld repair with heat treatment after the loop piping butter and with heat treatment after the weld repair.
4. A 50% inner diameter weld repair with heat treatment after the loop piping butter and with heat treatment after the weld repair.

The inner diameter repair was simulated as part of this analysis. The residual stresses resulting from the assembly process and inner diameter repair were calculated using an ANSYS™ finite element two-dimensional axisymmetric model.

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Two ANSYS library element types, PLANE55 and PLANE42 were used to create the finite element model. PLANE55 elements were used for the thermal analysis and PLANE42 elements were used for the structural analysis. PLANE55 is a 4-node two-dimensional thermal solid element with a single degree of freedom, temperature, at each node. PLANE42 is a 4-node two-dimensional structural solid element having two degrees of freedom per node: translation in the nodal x and y directions. These element types are appropriate for an axisymmetric evaluation using ANSYS. The same finite element mesh was used to evaluate both the thermal and structural loadings. Note that the global y-axis was oriented along the nozzle centerline and the global x-axis was in radial direction oriented axially 90 degrees° clockwise from the y-axis (required by ANSYS for axisymmetric evaluations).

All of the elements were included in the initial model and brought in and out of the solution using the "birth and death" capabilities in ANSYS. Temperature-dependent, nonlinear material properties along with the multi-linear kinematic strain hardening model were used in the analysis. The full length of the stainless steel safe-end and a sufficient length of the stainless steel pump nozzle and carbon steel loop piping were included in the finite element model to ensure end effects have no impact on the regions of interest. The models are shown in Figure 3-1.

The residual stress modeling was designed to match the actual welding process followed in the fabrication shop in Chattanooga, TN, as closely as possible. This information was obtained from the drawings as well as from interviews with personnel who worked there at the time, and were involved in the process. The piping segment was first buttered with Alloy 182, the nozzles welded in, and then the entire piece was heat treated. Following this process, the stainless steel safe-end which is approximately 5.125 inches long, was attached with Alloy 182 weld, to produce a single "V" weld. After the weld was completed, the inner portion of the weld was removed by grinding, to a depth of approximately 10% of the wall, and then the weld was completed from the ID. Note that this "original" or un-repaired configuration corresponds to a repair of 10% of the wall. Any repairs to this configuration would have been recorded, as they would have meant an interruption in the shop traveler schedule.

The finite element analysis consisted of a thermal solution followed by an elastic-plastic structural solution. The thermal solution was used to calculate the temperature response of the region of interest. The structural solution calculated the residual stress due to the temperature cycling from the assembly process. After each step of the assembly process the finite element model was allowed to cool to a uniform temperature of 70°F. After the loop piping buttering was simulated, a heat treatment was simulated in accordance with the temperatures required by the ASME Code, Section III Table NB-4622.1-1. The loop piping and attached buttering was raised to a temperature of 1,100°F, and then cooled to 70°F. This same process was repeated after the safe-end to loop piping inner diameter weld repair was simulated for cases 2 through 4. Hydrostatic test conditions were simulated after the assembly process was completed. A shakedown analysis was then conducted to demonstrate that the nozzle with weld repair do not continue to plastically deform after being cycled from ambient to operating conditions. The shakedown analysis consisted of four cycles of the assembly changing from ambient to operating conditions. Steady state operating conditions included a uniform temperature and a pressure loading of 2,235 psi on the internal surfaces. Steady state ambient conditions included a uniform thermal loading of 70°F and no pressure loading on the inside surfaces of the model.

The finite element model was created in ANSYS Workbench to take advantage of the modeling and meshing capabilities of Workbench. Workbench was then used to write an ANSYS input file to transfer the mesh to ANSYS, where the thermal and structural solutions were completed.

The results for the cases studied are summarized in Figures 3-2 and 3-3. The axial stresses shown in Figure 3-2 show a very similar pattern for all the cases, with stresses rather low at the inside surface, and then rising slightly over the depth of the assumed repair. Then, some distance into the wall beyond the repair, the stresses drop significantly to 15 to 20 ksi in compression. In the outer 20 percent of the wall, the stresses are very similar, rising gradually. Overall, the axial stresses are rather low.

The hoop stresses follow a similar pattern to that shown for the axial stresses, but they are generally significantly higher. The stresses are all positive at the inside surface, and then rise further with distance into the wall, before dropping off significantly at a distance somewhat beyond the depth of the repair. The 25% and 50% repairs drop the most, but in all cases the stresses remain positive.

3.3 VALIDATION OF RESIDUAL STRESS MODELING

The finite element modeling of the welding process was validated by comparison of calculated and measured residual stresses from a fabricated pressurizer safety nozzle. Although the pipe size is somewhat smaller, the methodology is the same.

Finite element analysis (FEA) of the weld residual stresses in a pressurizer safety nozzle to safe-end weld was completed, for two cases, before and after application of a structural weld overlay [29]. The results before the overlay was applied are more appropriate for presentation here, and they are provided in Figures 3-4 and 3-5, for axial and hoop residual stresses, respectively. The finite element analysis was completed prior to the experimental measurements; that is the experimental residual stress measurements were not used to develop the finite element analysis.

An elastic-plastic two-dimensional axisymmetric model was utilized to calculate the residual stresses through-wall at the centerline of the DM weld. The model utilized kinematic strain hardening and the temperature constraint method which greatly simplified the simulation as compared to detailed heat source modeling methods. The temperature constraint method holds the weld beads at near-melt temperature for a range of heat inputs where the range of heat inputs are controlled by the time at which the weld beads are held at temperature. Specifically, five different hold times, i.e., 0.1, 0.5, 1.0, 5.0 and 10.0 seconds, were utilized in the thermal solution to capture the effect of heat input on the simulation.

Figure 3-6 illustrates the FEA model used for the evaluation along with the stress path used for reporting results. For the simulations, the global y-axis was along the safety/relief nozzle centerline and the global x-axis was in the radial direction oriented axially 90º clockwise from the y-axis as is required by ANSYS for axisymmetric evaluations.

Residual stresses in the seven positions selected were measured through-wall with deep hole drilling (DHD) residual stress measurement techniques. Note that all measurements were performed starting from the mockup outer surfaces and progressed through the wall thickness to completion at the inner surface.

From Figures 3-4 and 3-5, it is evident that near the ID and OD surfaces of the mockup, there is good agreement between the measured and modeled results with excellent agreement throughout a majority of the mid-wall thickness. Note that near the ID and OD surfaces, the measured residual stresses are slightly more compressive than the modeled values.

While the residual stresses for this smaller thickness case compare very well with the measured values, the results for the thicker section of interest here are somewhat different due to the larger thickness and diameter. These differences are expected, which is the reason this additional work was performed.

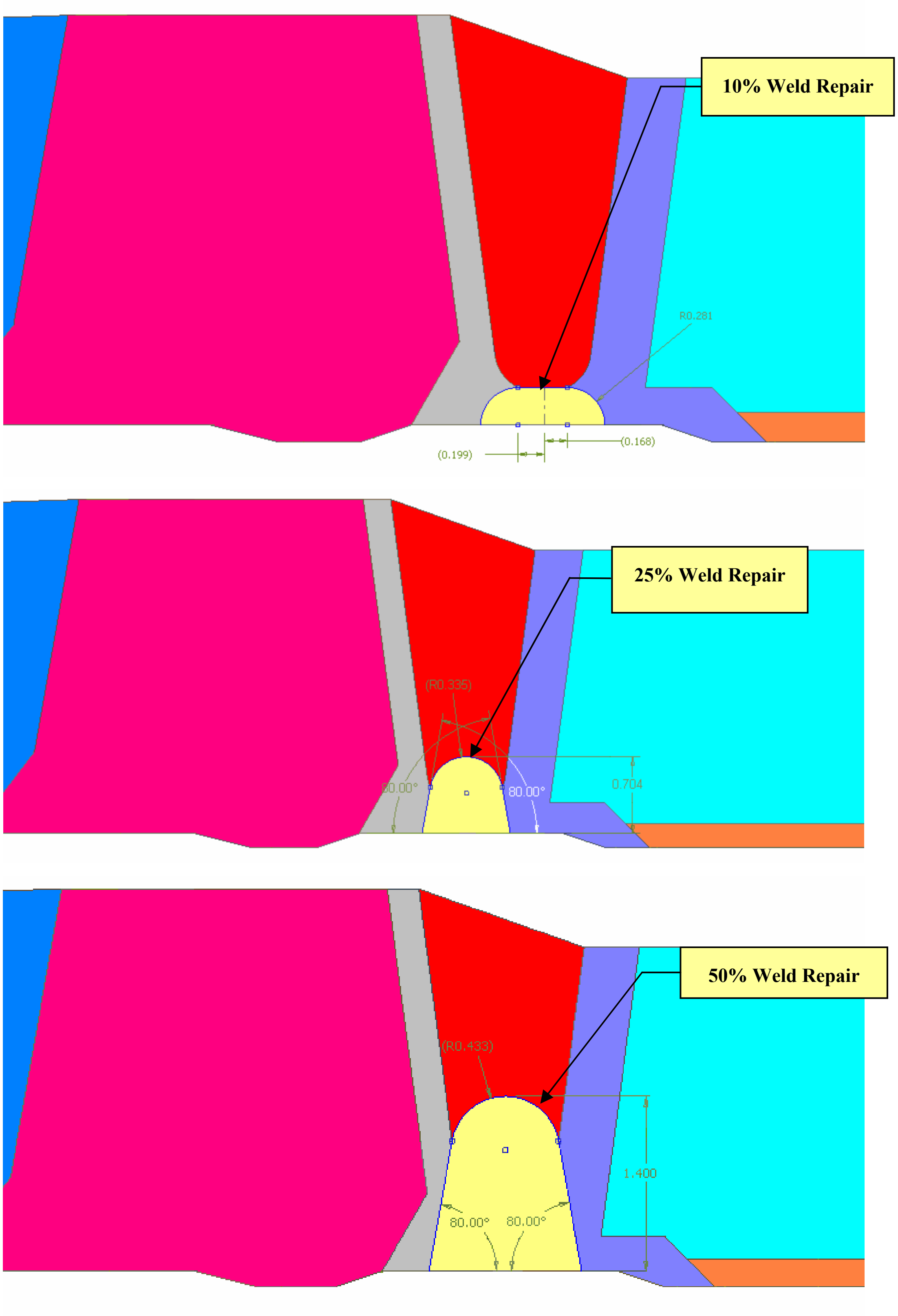

Figure 3-1: Finite Element Models of the Three Repair Configurations Modeled for the Pipe to Safe-end Weld

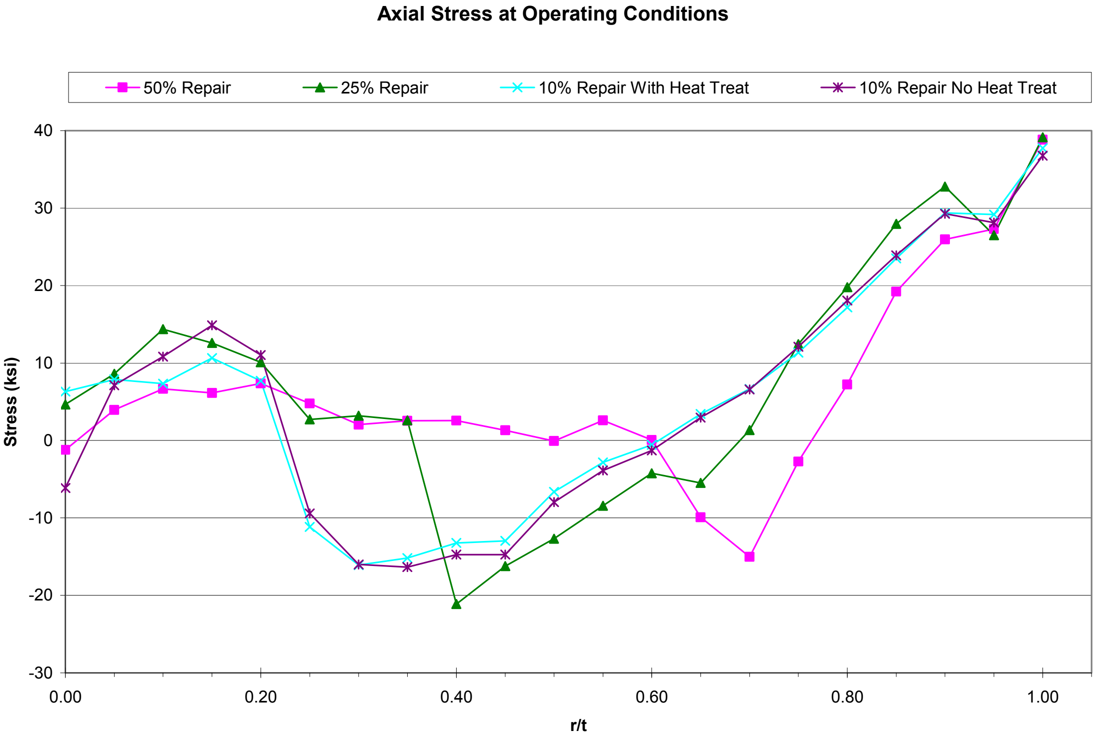

Figure 3-2: Axial Stress Results for All Cases Considered

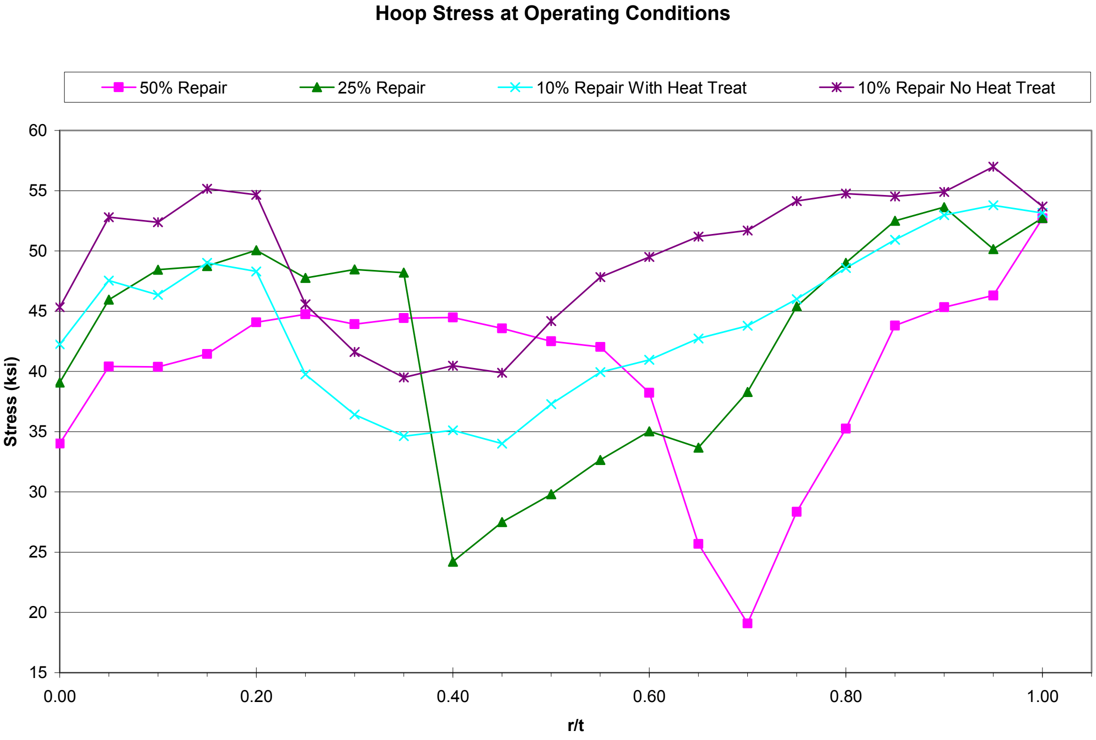

Figure 3-3: Hoop Stress Results for All Cases Considered

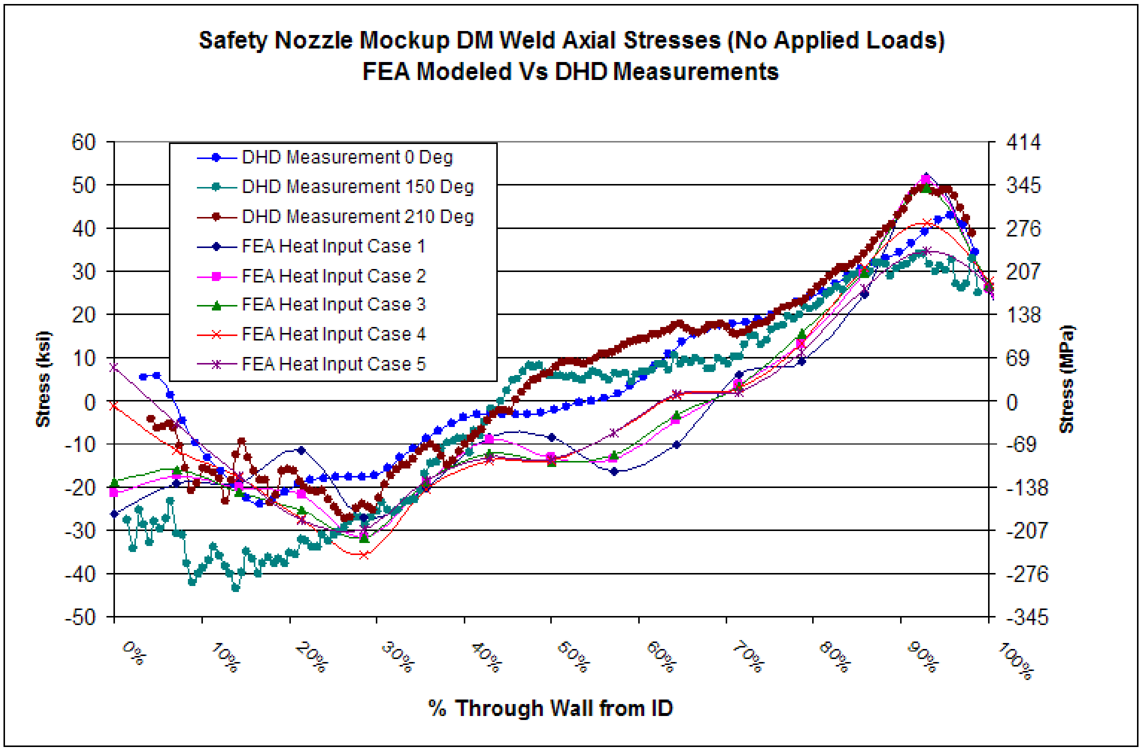

Figure 3-4: Axial Residual Stress Validation Results for the Pressurizer Safety Nozzle [29]

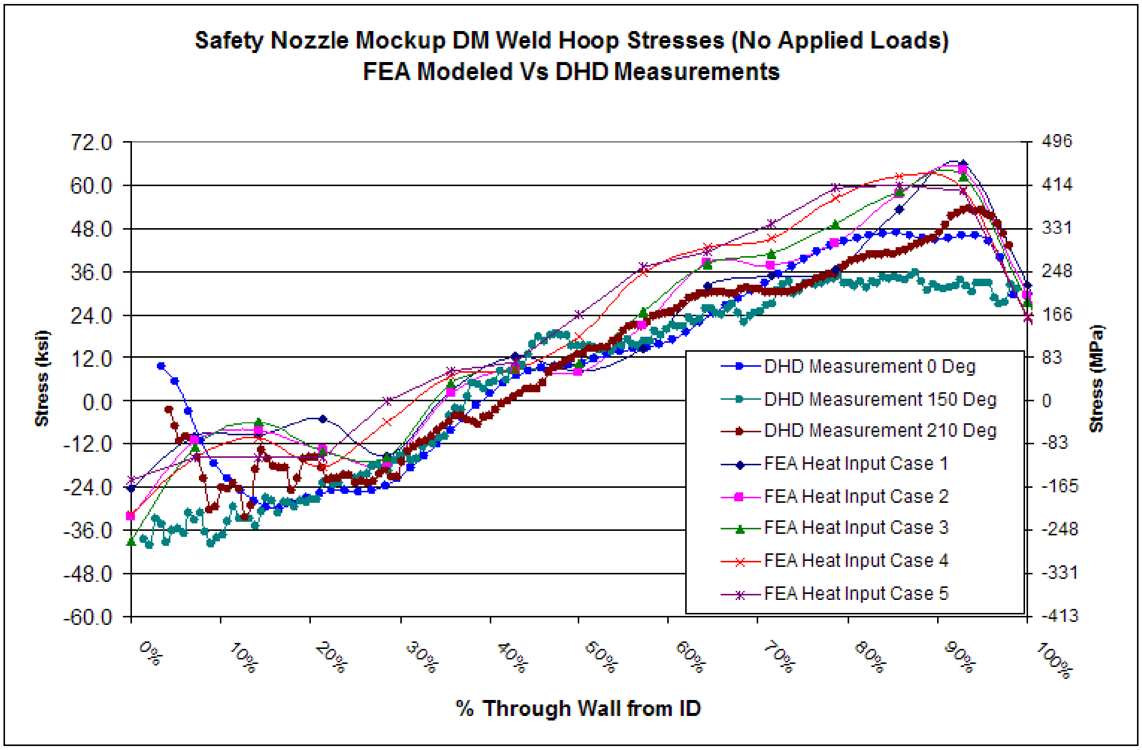

Figure 3-5: Hoop Residual Stress Validation Results for the Pressurizer Safety Nozzle [29]

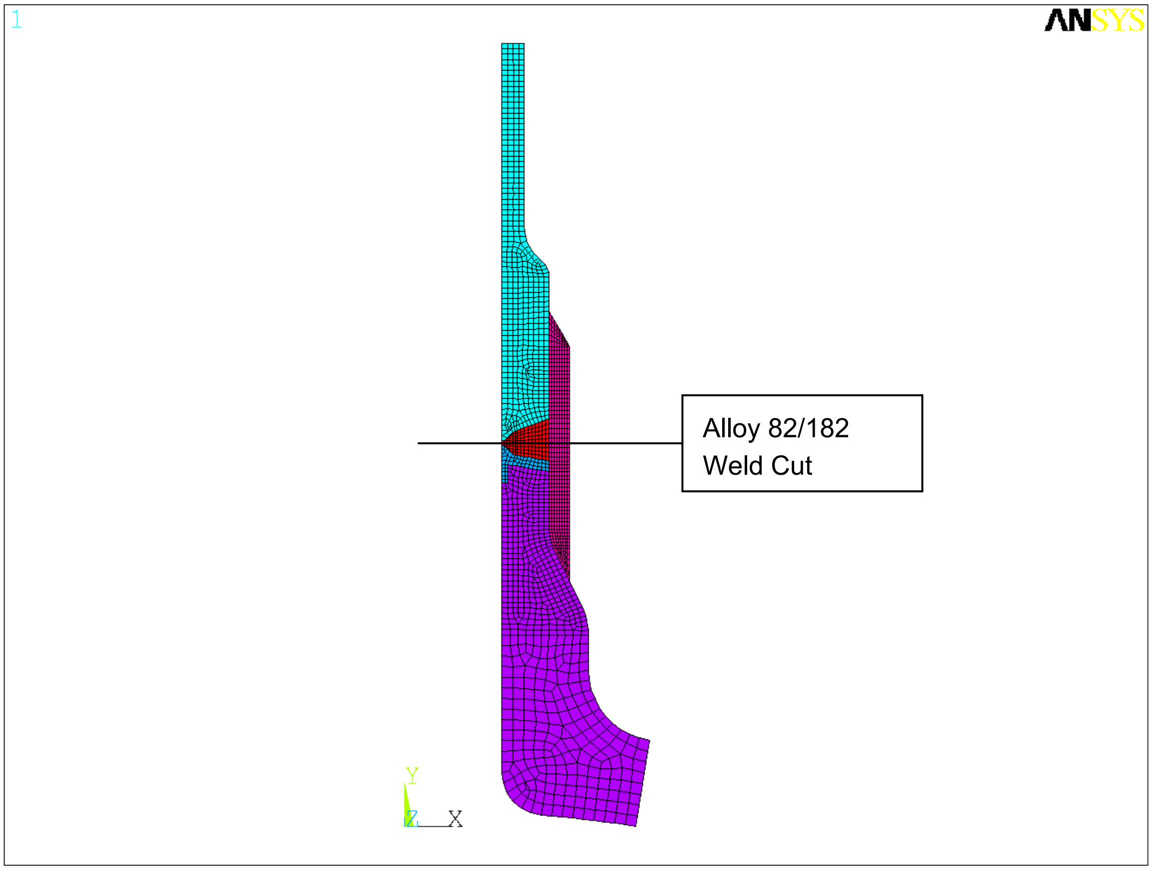

Figure 3-6: Finite Element Model Geometry for Pressurizer Safety Nozzle Validation [29]

4 SURVEY OF OBSTRUCTIONS FOR INSERVICE INSPECTIONS

4.1 INTRODUCTION

As described in the project authorization in [3], a letter request [4] was made to all participating utilities regarding information concerning obstructions to in-service inspections, as well as leak detection capabilities in the RCP suction and discharge nozzle regions. This request specifically consisted of the following:

- Plant leak detection capability as used in licensing activities,
- Plant leakage detection action levels,
- Obstructions to inspection, including the fillet radii, namely at small nozzle locations:
  - Circumferential as well as axial direction,
  - Location with respect to the Alloy 182 weld along the axial direction,
  - Location (angle) around the circumference of the cold leg with respect to the 12 o'clock position, and
  - "Permanent obstructions," such as piping branch connections, elbow intrados, instrument nozzles, etc.
- Operating temperatures, including changes over service history, for the:
  - Reactor vessel inlet nozzle,
  - Reactor vessel outlet nozzle, and
  - Reactor coolant pump suction and discharge nozzles,
- Inspection information, including the date of the latest UT inspection, and whether it was PDI qualified, for the:
  - Reactor vessel inlet nozzle,
  - Reactor vessel outlet nozzle, and
  - Reactor coolant pump suction and discharge nozzles.

The characterization of the uninspectable region with permanent obstructions should consider the inspection technique used its requirements, transducer widths, nozzle fillet radii, drawing tolerances, differences between the as-built configurations and the as-designed, weld contours, pipe whip restraints, and any other limitations that prevent the inspection.

This actual data is sought on the uninspectable area around the small nozzles near the RCP suction and discharge nozzle Alloy 182 weld locations on the cold leg. All the data obtained is described and summarized in Section 4.2.

4.2 SUMMARY OF PLANT OBSTRUCTIONS FOR INSPECTION DATA

Information on obstructions for in-service inspection has been summarized on a plant by plant basis. Estimates made by Westinghouse engineers were based on as-built drawings and supplemented the information obtained from surveys given to the plants.

Percentages presented are in terms of the percentage of the inside circumference.

Calvert Cliffs

The spray nozzle obstructs two of the RCP nozzles. While a customer report claims only 4.44% of the circumference is obstructed, Westinghouse estimates 11% obstruction.

ANO Unit 2

The spray nozzle obstructs two of the RCPs. An inspection completed in Fall 2009 achieved over 90% coverage.

Waterford Unit 3

A spray nozzle and one RTD cause obstruction. While a customer report provides no data regarding this obstruction, Westinghouse estimated a total of 10.7% + 1% = 11.7% obstruction. These are potentially connected depending on the RTD weld pad size. Consequently, the space between the spray nozzle and RTD need to be included.

St. Lucie Units 1 and 2

St. Lucie RCP nozzles have already been studied through direct sponsorship of a project from Florida Power and Light (FPL). Some photographs of St. Lucie nozzles are also available, but lack dimensional information. Previous estimates by FPL resulted in a maximum obstruction length of 23%, which includes the spray nozzle and RTDs.

Studies by WESDYNE were conducted to quantify the inspectable and non-inspectable regions. Spray nozzle obstruction and RTD nozzle reinforcement pads are not located far enough away from the DM welds and are, therefore, considered as obstruction for inspection. FPL is considering grinding the RTD pads to reduce the obstruction.

Millstone Unit 2

Millstone Unit 2, in their recent relief request submitted to the Nuclear Regulatory Commission (NRC), has identified a total volumetric coverage ranging between 73.1% to 80% for all 8 DM welds in their RCP nozzles.

SONGS Units 2 and 3

The four RCP discharge nozzles in the two SONGS units have different obstructions. One discharge nozzle has three RTDs (at 0, 45, and 315 degrees) only. Two RCP discharge nozzles have one charging or spray line attached at the 90-degree location, in addition to the three RTDs. The fourth pump has both a spray and charging nozzle at the 90-degree and 270-degree locations, in addition to the three RTDs. This results in a total of 24% circumferential obstruction. The UT limitation for each of the spray and charging nozzles is roughly estimated to be 11% of the circumference. These blind zones are separated from the RTD blind zone by an inspectable band approximately 24-degrees of pipe circumference. This was estimated from the photographs obtained from SONGS. Spray and charging nozzles are 180 degrees apart, so they do not need to be combined in the obstruction evaluation.

All Plants

A summary of obstruction estimates for the participating utilities is provided in Table 4-1 and summarized generically in Table 4-2.

Based on data available to date, it appears the SONGS plant has the most limiting case in percent coverage obstruction at one pump. There seems to be adequate space between the big nozzles and the RTD pads to consider these obstructions separate for SONGS. If one of the other plants (e.g. Waterford 3) has a large RTD nozzle pad, there may not be adequate space between the big nozzle and the RTD, then it might become the governing plant.

Per Westinghouse's survey of design drawings of RCP nozzles, the RTDs of many of the plants are more than 11 inches from the weld centerline, which is greater than two times the wall thicknesses plus the weld width, so the RTDs should not interfere.

4.3 ANALYTICAL ESTIMATION OF OBSTRUCTIONS

An analytical estimate of obstructions is obtained from design drawings, then compiled, and summarized in Table 4-1. This table lists various nozzles in the DM weld regions for all plants considered, and includes nozzle outside diameters, axial and circumferential lengths of the nozzle attachments, and the distance of the nozzle centerlines from the edge of the DM weld. When information was circulated to all participating utilities, the obstruction dimensions were increased by the size of the inspection transducer width of approximately 1 inch on either side of the nozzle. This information was used as a starting point for collection of obstruction data from participating plants in this study.

According to the analytical estimation, the largest circumferential obstruction angle occurs due to the safety injection nozzle attachment. Including the fillet radii on either side of the nozzle, a total of approximately 80° circumferential angle, or 22% of the circumference, is obstructed from in-service inspection (ISI). The next largest obstruction occurs due to charging and sprays nozzle attachments with approximately 40° or 11% of the circumference.

For the flaw evaluation, the largest obstruction assumed was 14% of the circumference, which is based on improvements planned or implemented by several participating utilities during the PWROG project.

Table 4-1: Summary of Obstructions for Inspection of CE Fleet RCP Nozzles from Drawings

Plant Name	Suction/ Discharge	Pipe OD (in)	Nozzle	Nozzle OD (in)	Axial Length (in)	Circumferential		Pump Weld Axial[2] (in)	Circumferential Location[1] (°)
						Length (in)	Angle (°)		
Constellation Calvert Cliffs 1 and 2	Discharge	35	SI	21.063	25.5	22.06	78.2	34.59	0
			Charging	7.375	10.88	10.88	36.2	50.56	270
			Spray	7.375	10.88	10.88	36.2	2.56	0
			RTD	7.125	7.125	7.125	23.5	4.44	45, 315
	Suction	35	Drain	Drain nozzle is far away from the DM weld and is not an obstruction.					
Dominion CT Millstone 2	Discharge	35	SI	21.063	25.5	22.06	78.2	34.78	0
			Charging	7.375	10.88	10.88	36.2	24.81	90
			Spray	7.375	10.88	10.88	36.2	2.75	0
			RTD	7.125	7.125	7.125	23.5	4.63	45, 315
	Suction	35	Drain	Drain nozzle is far away from the DM weld and is not an obstruction.					
Entergy ANO2	Discharge	36	SI	21.063	25.5	22.06	75.6	30.81	0
			Charging	7.375	10.88	10.88	35.2	51.88	270
			Spray	7.375	10.88	10.88	35.2	2.78	0
			RTD	0.993	0.993	0.993	3.2	7.72	45, 315
	Suction	36	Drain	Drain nozzle is far away from the DM weld and is not an obstruction.					
Entergy Waterford 3	Discharge	36	SI	21.063	25.5	22.06	75.6	30.63	0
			Charging	7.375	10.88	10.88	35.2	46.56	270
			Spray	7.375	10.88	10.88	35.2	3.56	0
			RTD	0.993	0.993	0.993	3.2	3.50	45, 315
	Suction	36	Drain	Drain nozzle is far away from the DM weld and is not an obstruction.					
FPL St. Lucie 1	Discharge	35	SI	21.063	25.5	22.06	78.2	34.59	0
			Charging	7.375	10.88	10.88	36.2	50.56	270
			Spray	7.375	10.88	10.88	36.2	2.56	0
			RTD	7.125	7.125	7.125	23.5	4.44	45, 315
	Suction	35	Drain	Drain nozzle is far away from the DM weld and is not an obstruction.					

Table 4-1: Summary of Obstructions for Inspection of CE Fleet RCP Nozzles from Drawings (continued)

Plant Name	Suction/ Discharge	Pipe OD (in)	Nozzle	Nozzle OD (in)	Axial Length (in)	Circumferential		Pump Weld Axial$^{(2)}$ (in)	Circumferential Location$^{(1)}$ (°)
						Length (in)	Angle (°)		
FPL St. Lucie 2	Discharge	35	SI	21.063	25.5	22.06	78.2	34.59	0
			Charging	7.375	10.88	10.88	36.2	50.56	270
			Spray	7.375	10.88	10.88	36.2	2.56	0
			RTD	7.125	7.125	7.125	23.5	4.44	45, 315
	Suction	35	Drain	See Note					
SCE SONGS 2 and 3	Discharge	36	SI	21.063	25.5	22.06	75.6	17.31	0
			Charging	7.375	10.88	10.88	35.2	2.56	90, 270
			Spray	7.375	10.88	10.88	35.2	2.56	90
			RTD	0.993	0.993	0.993	3.2	2.50	0, 45, 315
	Suction	36	Drain	Drain nozzle is far away from the DM weld and is not an obstruction.					

Notes:

SI = safety injection nozzle, RTD = resistance thermocouple detector

(1) Convention: standing on the ground, looking from the pump towards the pipe. 0° is at the 12 o'clock position; 90° is at the 9 o'clock, i.e., counter clockwise. See Figure 4-1. Also, see Figure 4-1 through Figure 4-4 for sample dimension conventions used for this table.

(2) Axial distance is measured from nozzle fillet edge to weld edge.

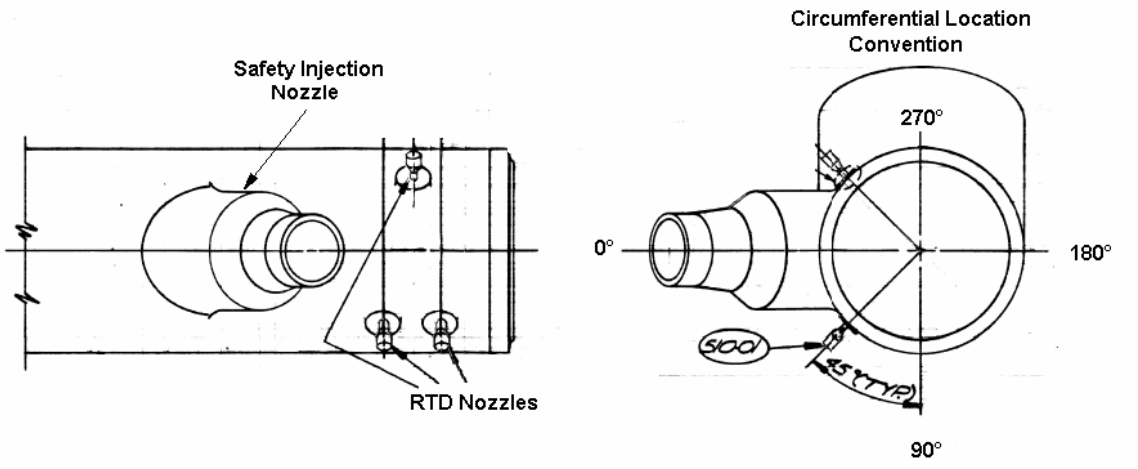

Figure 4-1: Nozzle Circumferential Location Convention

All dimensions are nominal. The width of the DM weld is approximated from the drawings. Figure 4-3 shows the dimension convention for each nozzle type.

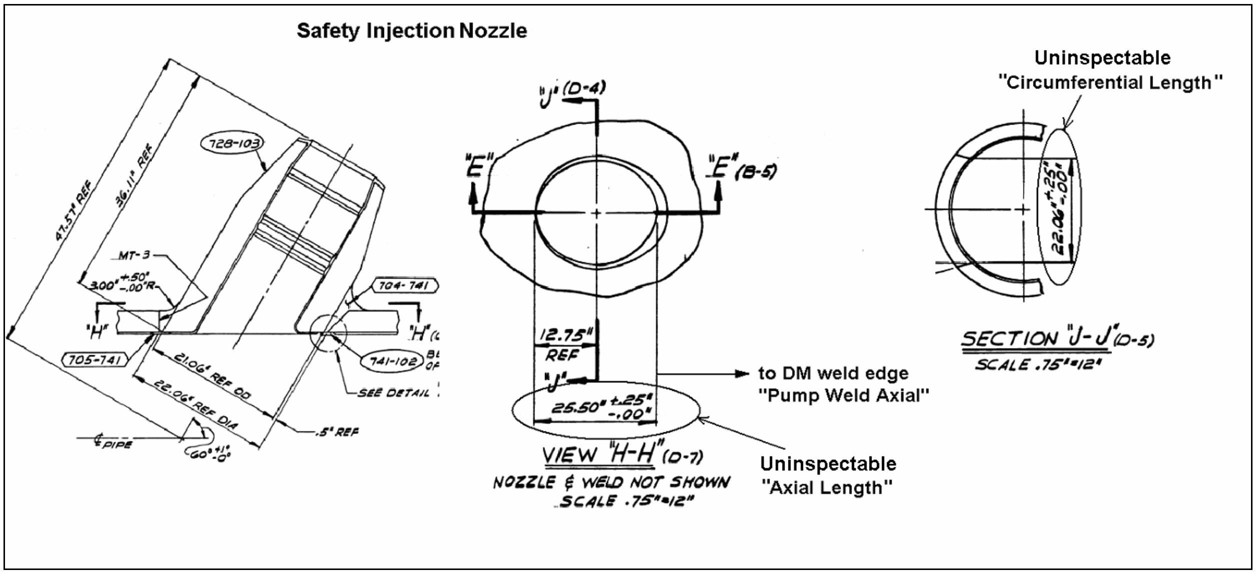

Figure 4-2: Sample Safety Injection Nozzle Uninspectable and Obstruction Dimensions

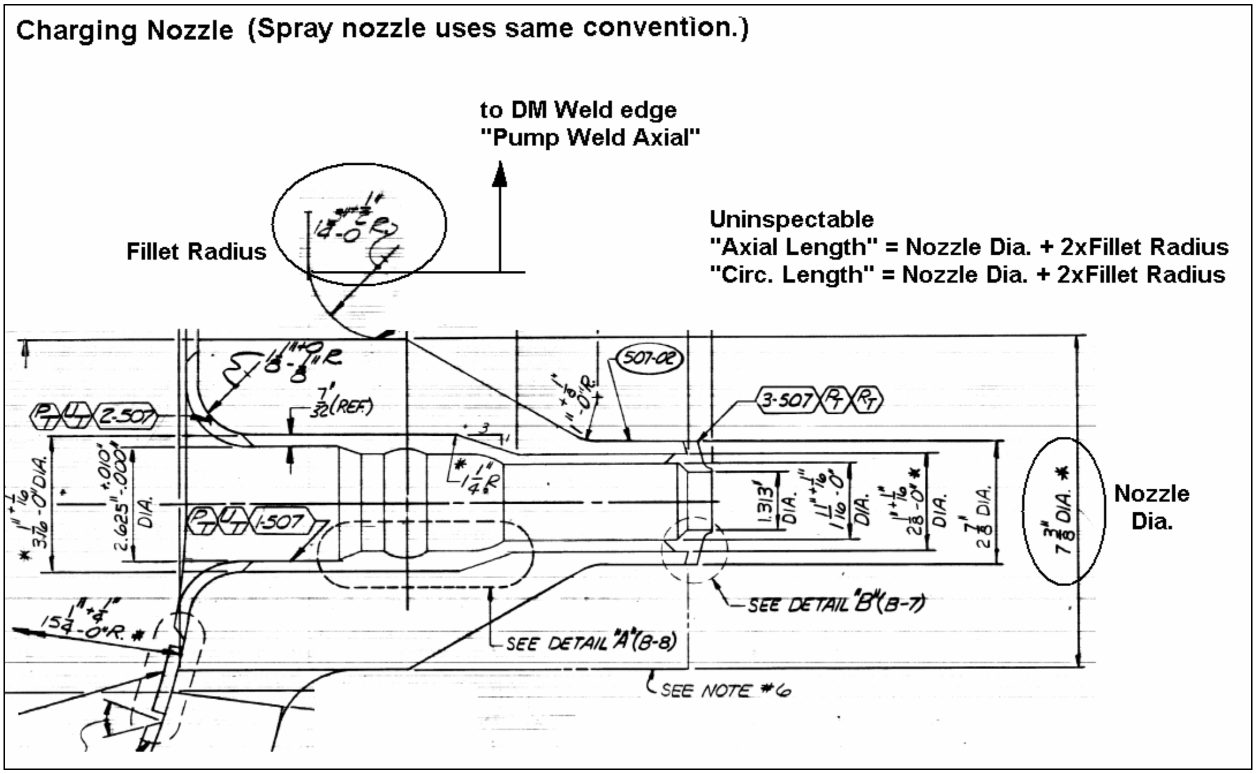

Figure 4-3: Sample Charging and Spray Nozzles Uninspectable and Obstruction Dimensions

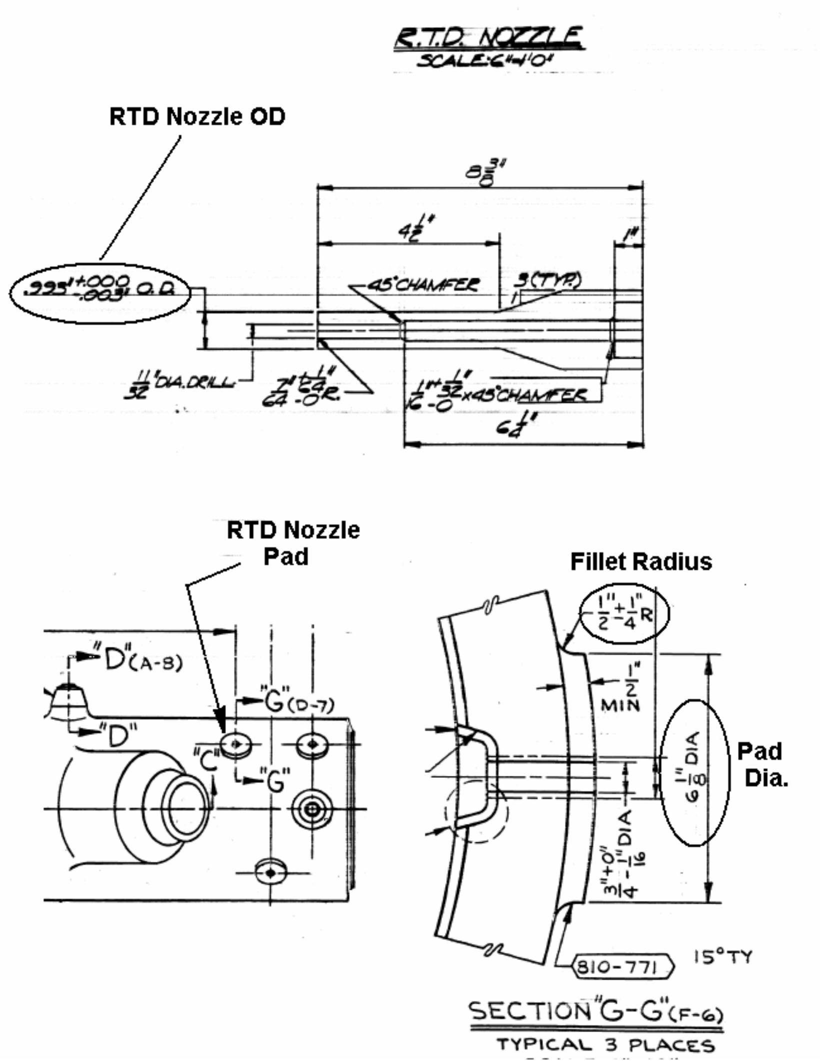

Figure 4-4: Sample RTD Nozzle Uninspectable and Obstruction Dimensions

Notes:

1. For the RTD nozzle without a pad, the uninspectable "Axial Length" and "Circumferential Length" is the outside diameter.
2. The "Pump Weld Axial" is the outside diameter edge to the DM weld edge.
3. For the RTD nozzle with a pad, the uninspectable "Axial Length" and "Circumferential Length" are the pad diameter plus two times the fillet radius.
4. The “Pump Weld Axial” is the edge of the pad fillet to the DM weld edge.

Table 4-2: Obstruction Region Estimated based on Enveloped Plant RCP Nozzles

Suction/ Discharge	Pipe OD (in)	Nozzle Type	Axial Length (in)	Circumferential Angle (°)
Discharge	35	SI	26	79
		Charging	12	40
		Spray	12	40
		RTD	7.1	23
Suction	35	No Obstruction		

5 JUSTIFICATION FOR DEVIATION FROM INSPECTION COVERAGE REQUIREMENTS: DEFENSE IN DEPTH

5.1 LEAK DETECTION CAPABILITY

After a number of recent operating events, the industry imposed an NEI-03-08 “needed” requirement, to improve their leak detection capability. As a result, virtually all pressurized water reactors (PWRs) in the US have a leak detection capability of less than or equal to 0.1 gpm. All plants also monitor seven day moving averages of reactor coolant system leak rates.

Action levels have been standardized for all PWRs, and are based on deviations from:

- The seven day rolling average,
- Specific values, and
- The baseline mean.

Action response times following a leak detection vary, based on the action level exceeded and range up to containment entry to identify the source of the leak. Utilities take the commitment of shutdowns due to unidentified leakage seriously. This is exemplified with utility shutdowns in July 2009, due to a 0.2 gpm leakage, and another in August 2009, with 0.09 gpm leakage. This improvement in leak detection sensitivity is due to multiple measures being monitored.

Leak rate action levels are identified in PWROG report, WCAP-16465 [24], and are below:

> Each PWR utility is required to implement the following standard action levels for RCS inventory balance in their RCS leakage monitoring program.
>
> A. Action levels on the absolute value of unidentified RCS inventory balance (from surveillance data):
> Level 1 - One seven day rolling average of unidentified RCS inventory balance values greater than 0.1 gpm.
> Level 2 - Two consecutive unidentified RCS inventory balance values greater than 0.15 gpm.
> Level 3 - One unidentified RCS inventory balance value greater than 0.3 gpm.
>
> Note: Calculation of the absolute RCS inventory balance values must include the rules for the treatment of negative values and missing observations.
>
> B. Action levels on the deviation from the baseline mean:
> Level 1 - Nine consecutive unidentified RCS inventory balance values greater than the baseline mean [μ] value.
> Level 2 - Two of three consecutive unidentified RCS inventory balance values greater than [$\mu + 2\sigma$], where σ is the baseline standard deviation.
> Level 3 - One unidentified RCS inventory balance value greater than [$\mu + 3\sigma$].

Information obtained about leak detection capabilities, detection levels, inspection obstruction regions, operating temperatures, and the latest inspection type and year regarding applicable plants is listed in Table 5-1.

5.2 LEAK RATE METHODOLOGY

As discussed earlier, the CE cold leg RCP nozzles have permanent obstructions that preclude the required, ultrasonic inspection coverage for circumferential flaws in the Alloy 82/182 welds. The combined calculated missed circumferential examination coverage ranges from 11% to 14% of the circumference. Since the action levels now employed by all the PWR utilities allow the early detection of small leakages, it is necessary to identify the extent of defense in depth this new sensitivity allows.

Quantifying the margins between leakage detection and the time required for the flaw to reach a critical length provides another measure of the flaw tolerance which exists in the RCP nozzle region.

Postulation of the initial through-wall circumferential flaws is determined based on leakage calculations consistent with current Nuclear Regulatory Commission (NRC) approved leak-before-break methodology [25]. Circumferential flaws yielding a leak rate of 0.1, 0.25, 0.5, 1.0, and 2.0 gpm were postulated as initial flaws for the current analysis. These leak rates are within typical nuclear power plant leakage detection capabilities, as discussed above.

The basic method used in the leak rate calculations was developed by Fauske [7] for the two-phase choked flow. To this, pressure loss due to friction upstream of the choked exit plane was added.

The flow rate through a crack was calculated in the following manner. Figure 5-1 [8] was used to estimate the critical pressure, P_c, for the primary loop enthalpy condition and an assumed flow. Once P_c was found for a given mass flow, the stagnation pressure upstream of the choked plane is obtained from Figure 5-2, which is taken from [8]. For all cases considered, the length to diameter ratio, $L/D_H > 40$, P_c/P_o, is equal to 0.55. Therefore, this method will yield a two-phase pressure drop due to momentum effects, as illustrated in Figure 5-3, where P_o is the operating pressure. Using the assumed flow rate, G, can be calculated as:

$$\Delta P_f = f \frac{(L/D_H - 40)G^2}{\rho 2 g_c (144)}, \qquad \text{Equation 5-1}$$

where

f = friction factor,
ρ = density of the fluid,
G = assumed flow rate,
L/D_H = length to diameter ratio of the pipe, and
g_c = acceleration due to gravity.

Here, f is determined using the Moody diagram. The crack relative roughness (ε) was obtained from fatigue crack data on stainless steel samples. The relative roughness value used in these calculations was 300 micro-inches root-mean-square (RMS). The frictional pressure drop using Equation 5-1 is then calculated for the assumed flow rate and added to the momentum pressure drop calculated using the Fauske model to obtain the total pressure drop from the primary system to the atmosphere for a given assumed flow rate, G.

$$\text{Absolute Pressure} - 14.7 = \Delta PT = (\Delta Pf + \Delta P_{2\phi} \text{ choked flow}) \qquad \text{Equation 5-2}$$

If the right-hand side of Equation 5-2 does not agree with the pressure difference between the primary loop and the atmosphere, then the procedure is repeated until Equation 5-2 is satisfied to within an acceptable tolerance, which in turn leads to a flow rate value for a given crack size.

Leak rate calculations were made as a function of crack length using the normal operating (NOP) loads provided in [5]. The NOP loads consist of the deadweight, thermal expansions, and pressure loads. Seismic loading is not included since it is an upset condition and also because it will result in a larger leakage flaw size for a given flow rate. The NOP loads for leak rate predictions are calculated by the following equations:

$F = F_{DW} + F_{TH} + F_P$
$M_X = (M_X)_{DW} + (M_X)_{TH}$
$M_Y = (M_Y)_{DW} + (M_Y)_{TH}$
$M_Z = (M_Z)_{DW} + (M_Z)_{TH}$

where,

DW = deadweight,
TH = normal thermal expansion, and
P = load due to internal pressure.

The stresses due to axial loads and bending moments in the leakage flaw size determination are calculated by the following equation:

$$\sigma = \frac{F}{A} + \frac{M}{Z} \qquad \text{Equation 5-3}$$

where,

σ = stress,
F = axial load,
M = moment,
A = pipe cross-sectional area, and
Z = section modulus.

The moments for the desired loading combinations are calculated by the following equation:

$$M = \sqrt{M_X^2 + M_Y^2 + M_Z^2} \qquad \text{Equation 5-4}$$

where,

M_x = X-component of the moment, torsion,
M_y = Y-component of the bending moment, and
M_z = Z-component of the bending moment.

The crack opening areas were estimated using the method of [9], and the leak rates were calculated using the two-phase flow formulation described above. The material properties at NOP temperature of 550°F were used for these calculations. The flaw sizes to yield a leak rate of 0.25, 0.50, 1.0, and 2.0 gpm were calculated using the computer code FHG [10, 11]. Crack opening areas to determine the leakage rates are calculated using the MPBK [10, 11] computer program. To account for the PWSCC crack morphology for the Alloy 82/182 weld leak rate calculation, a factor of 1.69 was applied to the leakage flaw size calculated for the fatigue crack morphology [12]. The results of the leakage flaw lengths for various leak rates are provided in Section 5.4.

5.3 CIRCUMFERENTIAL THROUGH-WALL CRITICAL FLAW SIZES - ASME SECTION XI, APPENDIX C

The critical through-wall circumferential flaw size determination is based on limit load methodology: the critical flaw size calculated is the circumferential flaw length required to cause pipe failure due to plastic collapse. The critical flaw lengths for through-wall circumferential flaws are also calculated based on Appendix C of ASME Section XI [1]. For flaws with circumferential angle $(\theta+\beta) \leq \pi$ as shown in Figure 5-4, the relation between the applied loads and flaw size at net plastic collapse is given by:

$$\sigma_b^c = \frac{2\sigma_f}{\pi}\left(2\sin\beta - \frac{a}{t}\sin\theta\right) \qquad \text{Equation 5-5}$$

$$\beta = \frac{1}{2}\left(\pi - \frac{a}{t}\theta - \pi\frac{\sigma_m}{\sigma_f}\right) \qquad \text{Equation 5-6}$$

where,

σ_b^c = bending stress at incipient plastic collapse,

θ = one-half of the final flaw angle,

β = angle to neutral axis of flawed pipe,

a/t = set to unity for through-wall circumferential flaws based on Code Case N-513-2 [1],

σ_f = flow stress = $\frac{S_y + S_u}{2}$, and

σ_m = applied membrane stress.

The allowable bending stress, S_c, used to calculate the maximum allowable end-of-evaluation period flaw sizes for the DM welds, is computed using:

$$S_c = \frac{1}{(SF_b)}\left[\frac{\sigma_b^c}{Z} - \sigma_e\right] - \sigma_m\left[1 - \frac{1}{Z(SF_m)}\right] \qquad \text{Equation 5-7}$$

where

S_c = allowable bending stress for circumferentially flawed pipe,

σ_b^c = applied bending stress at incipient plastic collapse,

σ_m = applied membrane stress,

σ_e = thermal expansion stress,

SF_m = safety factor for membrane stress (for Service Level A, B, C, and D, SF_m= 2.7, 2.4, 1.8, and 1.3, respectively),

SF_b = safety factor for bending stress (for Service Level A, B, C, and D,

SF_b= 2.3, 2.0, 1.6, and 1.4, respectively),

Z = $0.0000022(NPS)^3 - 0.0002(NPS)^2 + 0.0064(NPS) + 1.1355$, and

NPS = nominal pipe size.

The critical flaw length can then be determined by equating the applied bending moment at the nozzle to the allowable bending stress (S_c) in the above equation. It should be noted the "Z" correction factor from [1] is used, since it is representative of the Alloy 182 dissimilar metal weld of concern here. The results for the ASME limit load calculations are given in Section 5.4 for the pump suction and discharge nozzle DM welds.

5.3.1 Through-wall Circumferential Flaw Stress Intensity Factor Calculation

The axial stresses due to the normal operating loads from [5] (deadweight and thermal expansion) are combined with the residual stresses from [6] (illustrated in Figure 6-3) at the DM welds to determine the stress intensity factors for the through-wall circumferential flaw configuration. Once the stress intensity factors are determined, stress corrosion crack growth calculations can be performed using a PWSCC crack growth rate model developed in [13].

The bounding total stress (piping plus residual stresses) from the enveloped CE fleet RCP nozzle case were used to calculate the stress intensity factor (SIF) at the pump inlet and outlet nozzles. Recent literature solutions from Zang's paper in [14] for SIF expressions were used. These solutions provide representation of the through-wall stress distribution profile at the DM weld using a 4th order polynomial fit.

The stress intensity factors solutions from [14] were determined from a three-dimensional finite element model for through-wall cracks in cylinders. The axial stress distribution to calculate SIF can be determined by a 4th degree polynomial as follows:

for through-wall stress distribution,

$$\sigma(x) = A_0 + A_1 x + A_2 x^2 + A_3 x^3 + A_4 x^4 \qquad \text{Equation 5-8}$$

and for a global pipe bending moment,

$$\sigma(x) = \sigma_{gb}\left(\frac{z}{R_o}\right) \qquad \text{Equation 5-9}$$

where,

A_0, A_1, A_2, A_3, and A_4 = the stress profile curve fitting coefficients to be determined,

x = distance from the wall surface where the crack initiates,

z = radial distance to the point in the pipe wall thickness,

R_o = outer radius of the pipe,

σ_{gb} = maximum global bending stress at the outside surface of pipe, and

σ = axial stress.

The SIF for through-wall circumferential cracks due to the stresses defined above can be expressed as:

$$K_I = \sqrt{c\,\pi}\left[\sum_{i=0}^{4} A_i F_i + \sigma_{gb} F_5\right] \qquad \text{Equation 5-10}$$

where,

F_i, i = 1 through 4 are the normalized SIF influence coefficients for the polynomial stress fit coefficients,

F_5 = the influence coefficient for the global bending stress, and

c = the average half crack length around the circumference.

The normalized SIFs for through-wall stress distributions, F_i, i equals 1 to 4, have been further determined at the inside surface, intermediary locations, and outside surface of the cylinder. The normalized SIF have been calculated for the case of $t/R_{in} = 0.2$ (thickness to inside radius ratio), which most closely represents the pump inlet and outlet nozzle geometries. The SIFs were calculated as a function of crack length. These results will be used to generate PWSCC crack growth for various initial crack lengths in this section. The stress intensity factors for part-through flaws were determined from the work of Raju and Mehtu [19, 20].

5.4 RESULTS

Circumferential through-wall flaw lengths for various leak rates, ranging from 0.1 gpm to 2 gpm were calculated, for two cases, one for the minimum normal operating loads, and a second for the maximum normal operating loads. This is to cover the total leak rate crack lengths for the entire range of the RCP nozzles. The minimum normal operating load case results in a larger initial crack length and reaches the critical flaw length sooner, compared to the maximum normal operating case. This time period for a leakage flaw to reach critical crack size also depends on the other emergency and faulted loads as the latter determines the maximum critical crack lengths.

Table 5-2 lists initial total circumferential flaw lengths with various leak rates for the minimum and maximum normal operating loads. This table shows the leak rate flaws range from as small as 1.37 inches for a 0.1 gpm leak rate with maximum normal operating loads, to as long as 6.72 inches for 1.0 gpm leak rate with minimum normal operating loads. As all the CE plants listed in Table 5-1 have a leak detection capability of 0.1 gpm, initial crack sizes as small as 1.4 inch are of interest for the flaw growth.

Critical circumferential through-wall flaw sizes are computed for all the CE fleet RCP nozzles. As the normal, upset, emergency, and faulted loads vary considerably between various plants. Plant specific critical flaw sizes were computed for each plant as the enveloping load will be too restrictive for the rest of the plants. Table 5-3 shows the total circumferential crack lengths for the end-of-evaluation period. Any initial leak rate or assumed obstruction flaw propagation to these maximum lengths show the total time period available for inspection. This is discussed in the Section 6.

Calculations of the time to grow a crack from a length resulting in the actionable leak rate of 0.1 gpm to the critical length of a through-wall flaw showed that at least 14 years are required, an extremely large margin over the 12 hour maximum action time. This margin is shown graphically in Figure 2-2.

5.5 POTENTIAL FOR BORIC ACID CORROSION DAMAGE

The effect of potential reactor coolant leakage in this region was also assessed; although it seemed apparent that no such damage would occur. To complete the evaluation, it was assumed that a leak of 0.15 gpm occurred in the dissimilar weld of interest here. The reactor coolant temperature is assumed to be 560°F with a pressure of 2,235 psia. The maximum level of boric acid in the system would occur at the beginning of the fuel cycle and would be approximately 2,000 ppm boron.

There are a number of components and materials in close proximity to this weld:

- The pump body and safe-end materials (stainless steel at 550°F – 560°F)
- The reactor coolant piping (clad carbon steel at 550°F – 560°F)
- The supports for the pump (carbon steel at ~120°F)
- The concrete holding the supports (120°F)

Leakage through a crack in the weld of interest would result in the reactor coolant flashing to steam, but there is a potential for some liquid to remain in the mixture. Because the temperature of the pipe is 550°F – 560°F, the remaining liquid will quickly boil off, leaving dry boric acid. Therefore, there is concern for steam to escape and potentially condense on nearby equipment. The other hot locations would simply boil off any liquid that might land on them, but there is potential for damage to the cooler locations. Each location in question will be discussed below. Although the period of time over which the utility would take action is likely to never exceed seven days, a period of two months will be assumed here.

Stainless Steel: There is no impact because it is hot and resistant to damage.

Carbon Steel Piping: For this location, the only exposure would be to dry boron crystals. Reference [26] indicates no measurable corrosion at this temperature range (550°F – 560°F).

Carbon Steel Supports: The corrosion rate for carbon steel regions operating at 210°F is given in [26] as 4.8 inches/year for dripping boric acid. Since the supports are kept at 120°F or less by the Heating, Ventilation, and Air Conditioning (HVAC) system, this rate needs to be corrected for this lower temperature (120°F). Assuming the corrosion rate doubles for every 10°F, the resulting rate at 120°F would be < 0.010 inches/year. Therefore, the degradation of a support would be insignificant over the time of interest here.

Concrete: In most cases the concrete is coated, and so there is no direct contact with boric acid. For conservatism, this evaluation will consider the concrete to be in contact with the boric acid. Reference [27] indicates the depth of degradation may be modeled by:

$$\text{Depth} = C_o t^{0.5}$$

With $C_o = 0.00812$ inches/ $\text{day}^{0.5}$

For the 60 days of exposure assumed, the depth of the attack is 0.063 inches, which is insignificant.

Therefore, there is no concern for the degradation of any of the components which might be affected by a leak in the region of interest.

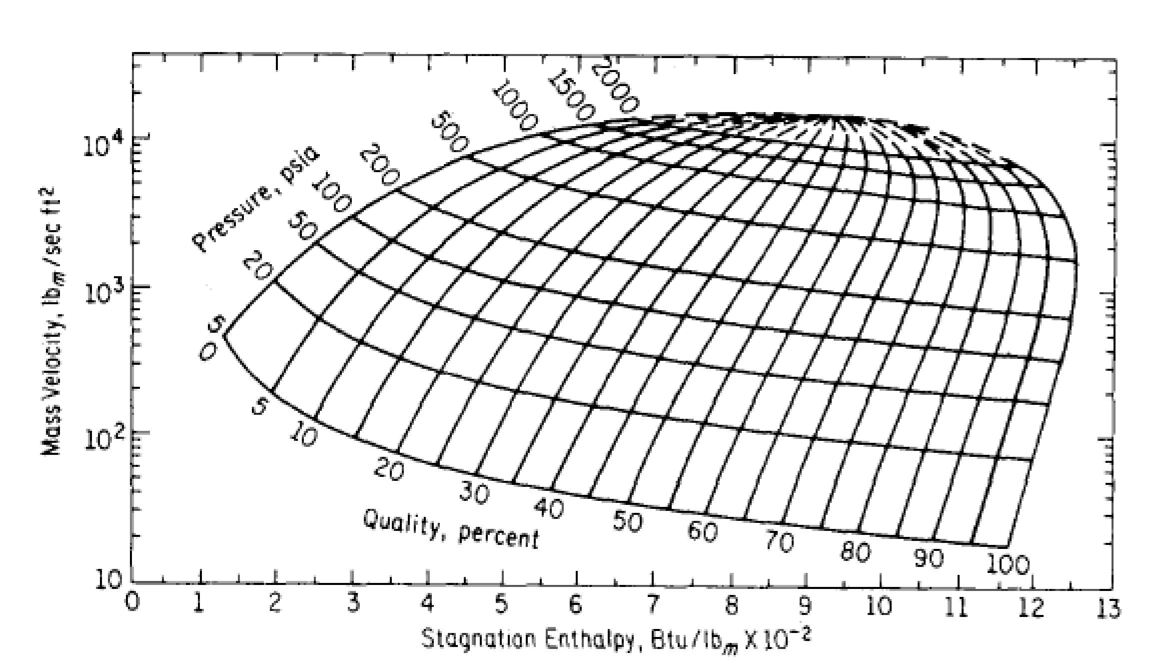

Figure 5-1: Analytical Predictions of Critical Flow Rates of Steam-Water Mixtures

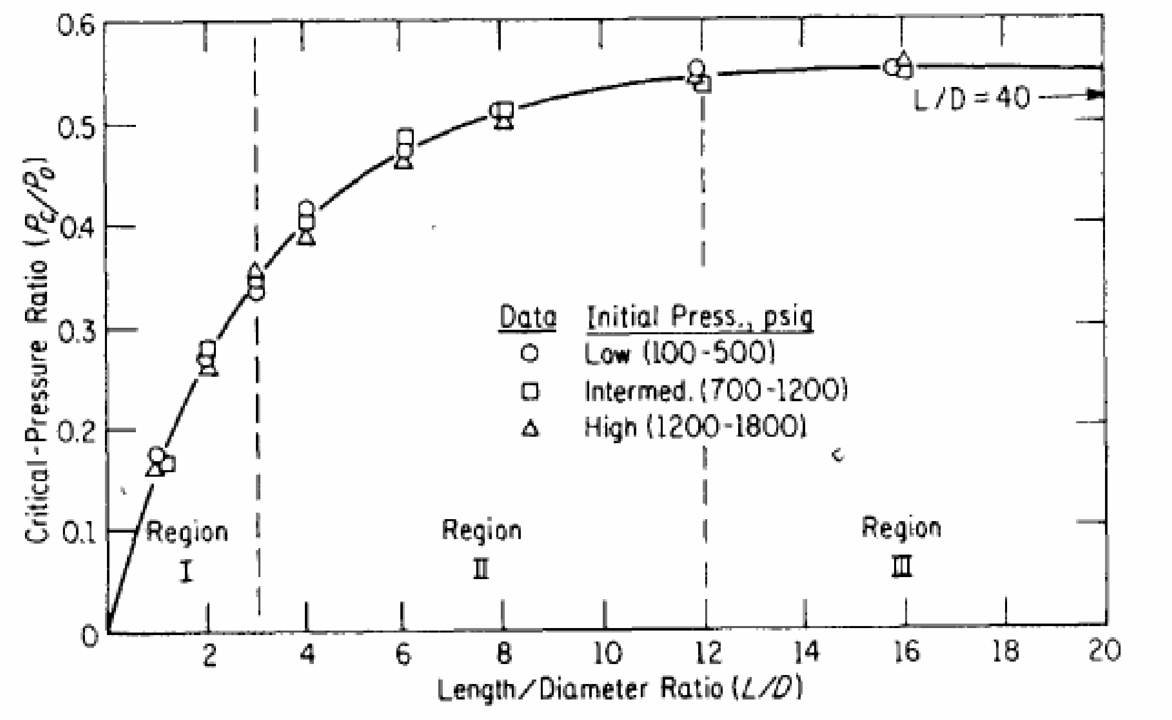

Figure 5-2: Critical or Choked Pressure Ratio as a Function of L/D

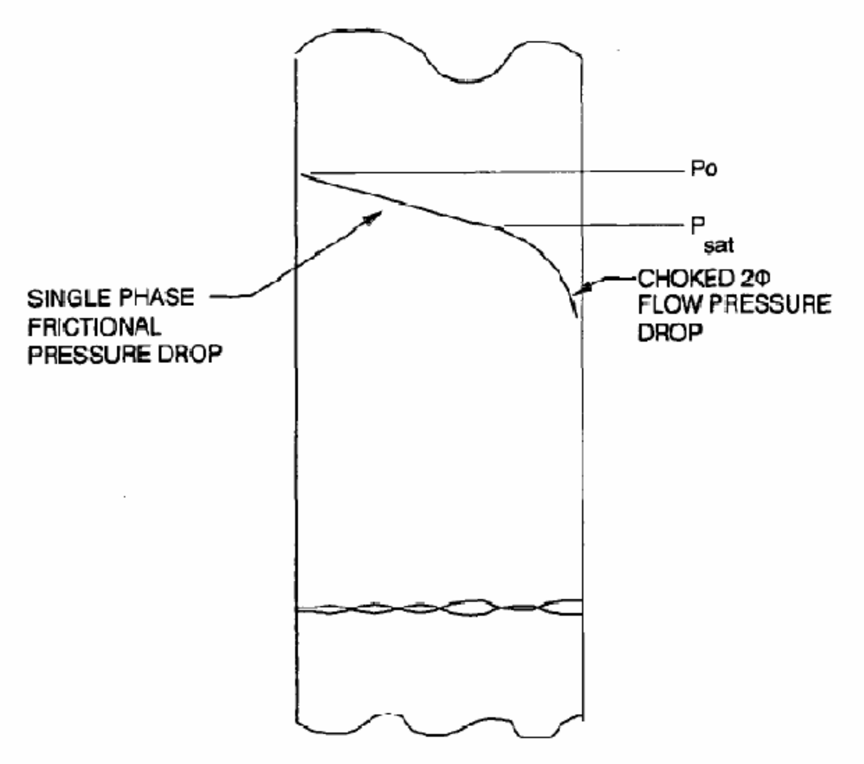

Figure 5-3: Idealized Pressure Drop Profile through a Postulated Crack

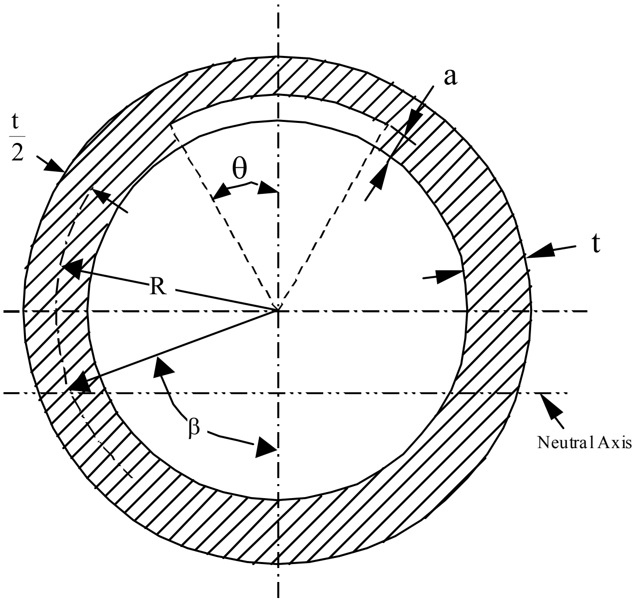

Figure 5-4: Circumferential Flaw Geometry

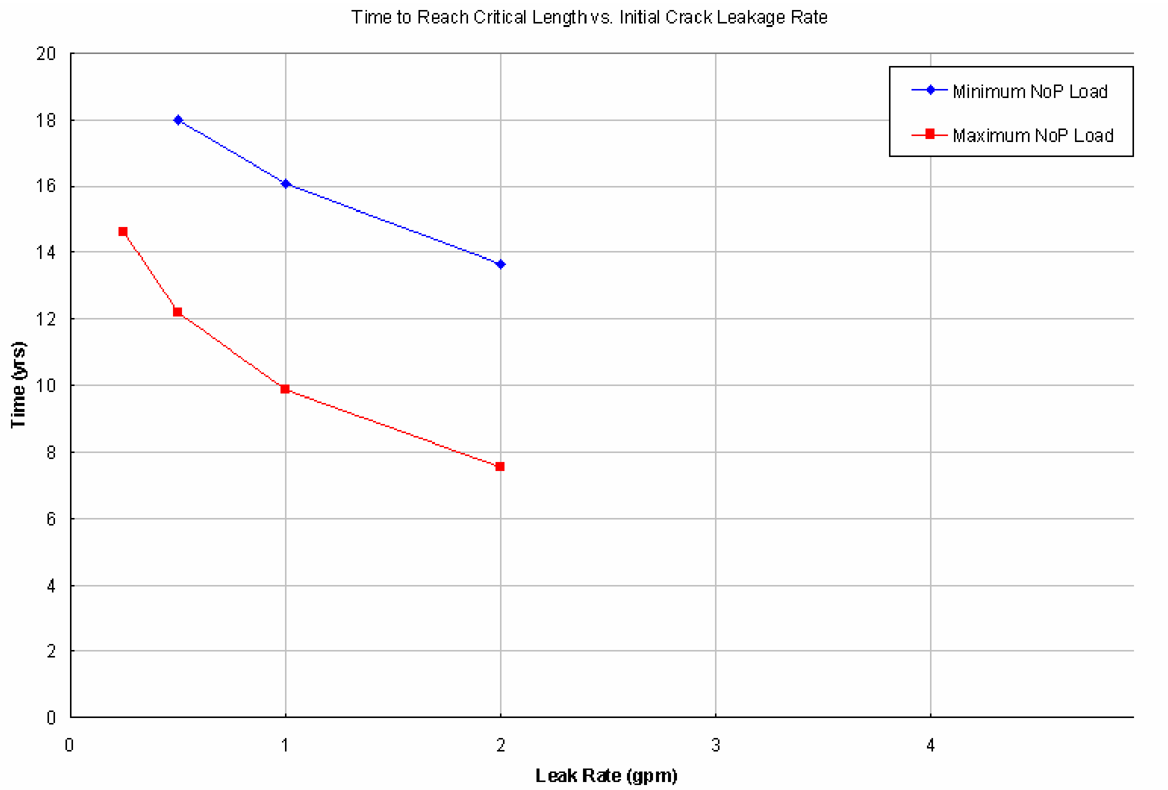

Figure 5-5: Time from Leakage to Critical Circumferential Flaw Length (No Residual Stress Case)

Table 5-1: Summary of Leak Detection Capability, Operating Temperatures, and Inspection Data

Plant Name	Leak Detection Capability Licensed (gpm)	Leak Detection Level (gpm)	Inspectable /Obstruction Region (%)	Operating Temperatures					
				RV Inlet Nozzle (°F)	RV Outlet Nozzle (°F)	RCP Suction (°F)	RCP Discharge (°F)	Latest Inspection, Year and Type	WEC Identified Obstruction$^{(1)}$ (%)
Constellation Calvert Cliffs 1 and 2	1 gpm for unidentified, 10 gpm for identified leakage	0.1 gpm for 7 day rolling average unidentified leakage	12.9% obstruction for ASME Section XI and 22.7% obstruction per MRP-139						11%
Entergy ANO 2	1 gpm for unidentified, 10 gpm for identified leakage	0.1 gpm for 7 day rolling average unidentified leakage	Over 90% coverage achieved			545.4°F to 553°F		Fall 2009 with PDI UT	10.7% by spray nozzle
Entergy Waterford 3	1 gpm	0.1 gpm for 7 day rolling average unidentified leakage	information on obstruction is not clearly identified		610°F	544°F average for all four cold legs			11.7% by spray nozzle
FPL St. Lucie 1 and 2	1 gpm	0.1 gpm for 7 day rolling average unidentified leakage				548.5°F to 550°F			11% by spray nozzle
SCE SONGS 2 and 3	1 gpm	0.10 gpm unidentified source	93% for RTD for all cold legs. 84% charging inlet based on 1 cold leg		594°F to 605°F	540°F to 553°F		PDI UT in 2002, non-PDI UT in 1996 and 1999	8% each by RTD and 11% each by spray and charging nozzles

Table 5-2: Initial Total Flaw Lengths for Various Leak Rates

	Maximum Normal Operating Load	Minimum Normal Operating Load
Leak Rate (gpm)	**Crack Length (in)**	**Crack Length (in)**
0.1	1.37	2.71
0.25	1.98	3.90
0.5	2.62	5.13
1.0	3.45	6.72
2.0	4.53	8.75

Table 5-3: Critical Circumferential Flaw Lengths Using the ASME XI Appendix C Approach

Plant	Limiting $2\theta_{crit}$ (°)	Limiting $2C_{crit}$ (in)
FP&L SL1 and 2	114.4	32.9
DC M2	86.5	24.9
CEG CC1 and 2	92.4	26.6
ANO2	104.8	30.2
W3	81.6	23.5
SONGS 2 and 3	71.7	20.7
Enveloped	71.5	20.6

6 FLAW TOLERANCE PER ASME SECTION XI

6.1 TRANSIENT ANALYSIS FOR THROUGH-WALL AXIAL STRESS DISTRIBUTION FOR USE IN FCG

The through-wall transient stresses for the RCP pipe to safe-end Alloy 82/182 DM weld were calculated using WESTEMS™. WESTEMS is a Westinghouse proprietary computer code, verified and configured for this type of analysis per [15]. WESTEMS permits the calculation of detailed stresses from pressure and thermal loads, as well as from externally applied forces and moments. Linear scaling of unit load finite element runs obtain stresses for mechanical cases (pressure, force, and moment). Time-dependent temperature profiles generate thermal loads using function integration. These temperature profiles utilize transfer function databases created with unit load (1°F) thermal analyses.

The stresses for the unit loading cases are calculated using ANSYS. ANSYS is a commercially available general-purpose finite element computer code, verified and controlled in the Westinghouse computer system [16]. ANSYS generates the transfer functions using non-temperature dependent material properties and constant values of heat transfer coefficients. Therefore, the WESTEMS results must be benchmarked. This benchmark compares generic transient results generated by WESTEMS with ANSYS-generated results with standard temperature dependent material properties. An adjustment factor from the comparison was used in the WESTEMS transient stress calculation.

The axisymmetric ANSYS Finite Element Model (FEM) conservatively models a typical dissimilar metal weld geometry with 30-inch inner diameter and 3 inch wall thickness. Physical properties [17] of the SA-516 Gr70 material were assigned to the carbon steel pipe; Alloy 82/182 properties were assigned for the dissimilar metal weld. The FEM and the ANSYS path, referred to as Analysis Section Number (ASN) in WESTEMS, is shown in Figure 6-1. WESTEMS™ provides the through-wall transient stresses in a format that can be used in the fatigue crack growth analysis.

As Figure 6-1 shows, the bottom end of the ANSYS model is constrained in the Y-direction for the pressure and thermal/mechanical analyses. Blow off pressure is applied at the top end of the model for pressure analysis to simulate the rest of the piping system. For the thermal/mechanical analysis, nodes at the top end of the model are coupled in the Y-direction to simulate a long pipe.

The cut defined at the middle of the Alloy 182 weld was divided into ten equally spaced sections and contains eleven nodes through the cut. Figure 6-1 shows the ASN location on the model. For the heat transfer analysis, a conservative film coefficient (4,384 BTU/hr-ft^2-°F) was applied to the inside surface of the pipe. The outside surface was conservatively assumed to be insulated. The temperature of the inside surface is increased by 1°F in one second. The case is then run to 10 hours, where the model reaches equilibrium. The postulated temperature time-history transients are applied in WESTEMS. The thermal stresses are calculated using the transfer function method.

™ WESTEMS is a trademark of Westinghouse Electric Company, LLC.

The mechanical pipe loads used in the WESTEMS analysis are provided in [5]. Both the maximum and the minimum applied loads are considered in this analysis. For piping loads, only the axial force and bending moment are considered, since the effect of shear stress on crack growth is insignificant.

6.2 PWSCC GROWTH CALCULATIONS

The CE design pump nozzle to safe-end dissimilar metal weld region is made of nickel based alloys. This nickel based alloy material (Alloy 82/182) is susceptible to the PWSCC growth mechanism. Once the stress intensity factors are determined, PWSCC crack growth can be calculated based on the applicable ASME Code recommended crack growth curves for PWSCC [13]. The recommended PWSCC growth curve for Alloy 182 material is as follows:

$$\frac{da}{dt} = \exp\left(-\frac{Q_g}{R}(1/T - 1/T_{ref})\right)\alpha(K)^{\beta} \qquad \text{Equation 6-1}$$

where:

$\frac{da}{dt}$ = crack growth rate in m/sec,

Q_g = thermal activation energy for crack growth = 130 kJ/mole (31.0 kcal/mole),

R = universal gas constant = 8.314 x 10^{-3} kJ/mole-K (1.103 x 10^{-3} kcal/mole-°R),

T = absolute operating temperature at the location of crack, °K (°R),

T_{ref} = absolute reference temperature used to normalize data = 598.15°K (1,076.67°R),

α = crack growth amplitude = 1.50 x 10^{-12} at 325°C (617°F),

β = exponent = 1.6, and

K = crack tip stress intensity factor (MPa√m).

The pump outlet nozzle nominal operating temperature was taken as 550°F [22]. This temperature is used in the fracture mechanics analyses. The stresses used for PWSCC evaluations included normal operating condition piping stresses and pressure. The PWSCC growth rate was determined as shown below, where K is in units of psi√in and the resulting growth rate is in units of inches per hour.

$$\frac{da}{dt} = 6.925 \times 10^{-13} (K)^{1.6} \qquad \text{Equation 6-2}$$

Typical crack tip stress intensity factors across the nozzle thickness for various circumferential through-wall crack lengths are plotted in Figure 6-4. The figure also consists of enveloping the maximum, as well as an averaged SIF across the nozzle wall thickness. These represent the maximum and average crack driving forces occurring in the wall for circumferential crack propagation. Here, after comparison with the detailed three-dimensional FEACrack™ analysis of crack propagation under PWSCC conditions, described in Section 7, the average SIF was chosen for the PWSCC growth evaluation. Results of the evaluation for the maximum normal operating loads with various initial crack sizes are shown in Figure 6-5. These initial crack sizes represent different leak rates, as well as the average maximum obstruction of 11% of the nozzle outside circumference.

6.3 FATIGUE CRACK GROWTH CALCULATIONS

The through-wall stress distributions used in the crack tip SIF calculation were determined by combining the stresses from the plant operating transients with the residual stresses. The axial and hoop residual stresses used in this evaluation are from MRP-113 [6]. The residual stresses at ambient temperature were conservatively assumed for both ambient and normal operating conditions. It is assumed the residual stresses remain unchanged for the entire duration of plant life.

At each time step, crack tip SIFs were computed for each transient. Full-circumferential part-through-wall flaws were considered in the evaluation. To compute the SIFs for axial and circumferential flaws, Raju-Newman and NASA solutions from [19 and 20] were used.

Once the SIFs were computed for each transient, the maximum and minimum SIFs for various flaw depths were determined. Then, these minimum and maximum SIFs were curve-fit separately into a 6th-order polynomial as a function of flaw depth. Finally, the resulting polynomials were used in the fatigue crack growth (FCG) evaluation.

The FCG analysis procedure involves postulating an initial flaw at the region of concern. Postulated flaws are subjected to cyclic loads due to transients. The input required for an FCG analysis is the range of crack tip SIFs, ΔK. ΔK depends on the crack size, crack shape, geometry of the structural component where a crack is postulated, and the applied cyclic stresses. Also, load ratio, $R = K_{min}/K_{max}$, is required for the scaling parameter in the crack growth model.

Once R and ΔK are calculated, the crack growth due to any given stress cycle can be calculated. Then, this increment of crack growth is added to the original crack size, and the analysis proceeds to the next transient. The procedure is continued in this manner until all the transients known to occur in the period of evaluation have been analyzed. The design transient load cycles were based on a 40-year plant design life. The crack growth for each transient for a given time interval can be computed using the following equation:

$$a_{i+1} = a_i + \Delta a \qquad \text{Equation 6-3}$$

The incremental crack depth is given by:

$$\Delta a = \left(\frac{da}{dN}\right)_{env} (N) \qquad \text{Equation 6-4}$$

™ FEACrack software is a trademark of Quest Reliability, LLC.

Fatigue crack growth was calculated based on the through-wall K_{max} and K_{min} polynomials and the design transient cycles.

The general crack growth rate for Alloy 182 materials in PWR environments are given by:

$$\left(\frac{da}{dN}\right)_{env} = F_{weld} F_{env} C(T) S(R) (\Delta K)^n \qquad \text{Equation 6-5}$$

where,

$C(T)$ = scaling factor for temperature effects,
$S(R)$ = scaling factor for load ratio effects,
F_{weld} = factor for weld material,
F_{env} = factor for environment,
ΔK = SIF range = K_{max} - K_{min}, MPa√m (ksi√in),
R = load ratio K_{min} / K_{max},
K_{max} = maximum SIF, MPa√m (ksi√in),
K_{min} = minimum SIF, MPa√m (ksi√in),
$\left(\frac{da}{dN}\right)_{env}$ = crack growth rate in environment, m/cycle (inch/cycle), and
n = crack growth law exponent.

The crack growth rate reference curves for the Alloy 82/182 weld have not been developed for Section XI in the ASME Code; therefore, information available from the literature was used. Based on the results reported in [21], the parameters for the crack growth model for Alloy 82/182 material are:

$$C_{A600} = 4.835 \times 10^{-14} + (1.622 \times 10^{-16})T - (1.490 \times 10^{-18})T^2 + (4.355 \times 10^{-21})T^3 \qquad \text{Equation 6-6}$$

$$S = (1 - 0.82R)^{-2.2} \qquad \text{Equation 6-7}$$

$$F_{env} = 1 + A\,[CS\Delta K^n]^{m-1} T_R^{1-m} \qquad \text{Equation 6-8}$$

$$F_{weld} = 10$$

where,

T = temperature (°C),
ΔK = SIF range, MPa√m (ksi√in),
K_{max} = maximum SIF, MPa√m (ksi√in),
K_{min} = minimum SIF, MPa√m (ksi√in),
n = crack growth law exponent (= 4.1),
A = constant in crack growth law for Alloy 82/182 weld (= 4.4×10^{-7}),
m = exponent in crack growth law for Alloy 82/182 weld (= 0.33),
T_R = rise time, seconds, and
F_{weld} = factor for weld.

The values for A and m in Equation 6-8 are provided in [21] through a least-square curve fitting of the FCG data on Alloy 82/182 material in high-purity water with ~300 ppb dissolved oxygen. For the Alloy 82/182 material, $F_{weld} = 10$ is used to determine the FCG. The basis for the crack growth rate (CGR) curves from [21] is shown in Figure 6-2.

The transient stresses from the WESTEMS analysis discussed previously were used in the fatigue crack growth calculations. The fabrication weld residual stresses from [6] are then added to the transient stresses. Then, each of the transient stress was evaluated for through-wall crack tip SIFs at various transient time steps and cyclic minimum and maximum values- captured for different flaw lengths. Typical values for the heatup transient are shown in Figure 6-6. This procedure was followed for all the transients. Then the fatigue crack growth evaluation was performed, and results are summarized in Figure 6-7. This figure shows the results for a through-wall circumferential flaw for various initial crack sizes. It can be seen from this figure that fatigue crack growth is considerably slower than the PWSCC growth, indicating the later to be the predominant mechanism.

Additionally, a fatigue crack growth analysis was performed for an ID surface flaw, using WES_FRAMES [18]. The residual stresses from [6] were used. Initial flaw depths ranging from 50% to 100% of the wall thickness were evaluated. A total of six cases were considered:

1. Maximum pipe load with no residual stress,
2. Minimum pipe load with no residual stress,
3. Maximum pipe load with residual stress, no ID weld repair,
4. Minimum pipe load with residual stress, no ID weld repair,
5. Maximum pipe load with residual stress and ID weld repair, and
6. Minimum pipe load with residual stress and ID weld repair.

As shown in Figure 6-9 through Figure 6-12, the results of fatigue crack growth is negligible for surface flaws with initial flaw depths below 60% wall thickness. For initial flaw depths greater than 60% wall thickness, the effect of FCG is small, but measurable. Therefore, for the surface flaws which are of interest to the evaluations discussed in this report, fatigue crack growth can be ignored.

6.4 COMBINED PWSCC AND FATIGUE CRACK GROWTH EVALUATION

Since fatigue crack growth for through-wall flaws was found to make a meaningful contribution to the total growth, a methodology was developed to allow calculation of the combined growth from both fatigue and PWSCC. (Note this was not necessary for surface flaws, since growth was negligible.)

While PWSCC occurs throughout the operating period between the outages, fatigue crack growth occurs only when the transient cycle is being applied during operation between the outages. Also, the actual timing of the transient occurrence is not known in advance and may vary from outage to outage and plant to plant. To start the analysis, a sequential flaw growth with PWSCC was assumed to occur continuously for one year. This was followed by fatigue crack growth for all the cycles over the course of a one-year period. First, Equation 6-1 was applied for the

PWSCC growth for one year. Then, the FCG was evaluated using Equation 6-5 for all the transient cycles per year. The process was then continued, and total crack growth was then plotted on a yearly basis.

Typical results for the combined crack growth are shown in Figure 6-8. The combined crack growth indicates, for example, an initial 11% circumferential length flaw grows to approximately a total crack length of 20.6 inches in 4.7 years compared to about seven years if only PWSCC growth was considered. The most limiting critical circumferential flaw length for the CE fleet with maximum applied piping loads is 20.6 inches. For the least severely loaded plant, the critical length is as high as 33 inches. For the latter case, an initial flaw of 11% circumferential through-wall reaches the critical length in approximately seven years under the combined PWSCC and fatigue crack growth mechanism.

6.5 ASME SECTION XI FLAW TOLERANCE CALCULATIONS

The flaw evaluation performed in Phase I of the PWROG study [22] revealed that these nozzles operating at cold leg temperatures have considerable flaw tolerance, but the results were limited to a two-year service period. This was because only PWSCC growth was considered, and for longer time periods, it was thought fatigue crack growth could play a role. With the present study, both fatigue and PWSCC growth have been evaluated. Therefore, the flaw tolerance evaluation can be extended to longer service periods.

As discussed in Section 5.3 of this report, the allowable flaw depth has been determined from the governing loads, as a function of the flaw shape. Fatigue crack growth has been determined to be negligible, so the PWSCC results will govern the flaw tolerance. Both axial and circumferential flaws were evaluated, and the results are presented in terms of the largest initial flaw, which is acceptable for a range of time periods. The results presented here are for periods of 24, 36, and 48 months, but the evaluations could be easily extended to justify the acceptability of a smaller flaw, should one be discovered during an in-service inspection.

The maximum allowable flaw size, per Appendix C of Section XI [1], is not affected by residual stresses, since the material is ductile. However, since PWSCC is the dominant mechanism of growth for flaws in this region, the residual stresses will affect the growth. A design-specific finite element analysis was completed, and is discussed in detail in Section 3 of this report. Four cases were studied:

- Fabrication plus a 10% ID repair,
- Fabrication plus a 10% ID repair, with post weld heat treatment (PWHT),
- Fabrication plus a 25% ID repair, with PWHT, and
- Fabrication plus a 50% ID repair, with PWHT

Repair induces compressive axial residual stresses in the mid-wall region, just beyond the repair. The closure weld is therefore effectively a mitigation, causing compressive axial stresses at the pipe's ID, thus essentially preventing crack initiation. The hoop stresses are depressed as well, as result of the closure weld, but not as severely as the axial stresses. This is consistent with the results on closure welds in smaller diameter pipes [23].

The allowable flaw depths for both the suction and discharge nozzles are very large. For axial flaws, the allowable depth ranges from 60 to 75 percent of the pipe wall thickness, depending on the flaw shape. For circumferential flaws, the allowable depth ranges from 73 to 75 percent of the thickness, depending on the flaw shape.

Flaw evaluation charts were developed for the region of interest, using the design-specific residual stresses described in Section 3, and a series of figures was prepared to cover a range of repair scenarios. These charts all have the same character, and are designed to allow quick evaluation of indications which may be identified during inspection. The curves in the charts were determined fron PWSCC calculations, and include the effects of fatigue crack growth, which was found to be negligible.

Once an indication is identified, it must be characterized as to its location, length (l) and depth dimension (a). This characterization is discussed in further detail in Article IWA 3000 of Section XI[1].

The following parameters must be calculated from the above dimensions to use the charts (see Figure 6-13 for example):

Flaw Shape Parameter,	a/l
Flaw Depth Parameter,	a/t

where

t = wall thickness of region where indication is located

l = length of indication

a = depth of surface flaw; or half depth of embedded flaw in the width direction

Once the above parameters have been calculated, these two parameters for each indication allow a point to be plotted directly on the appropriate evaluation chart. Their location on the chart determines the acceptability immediately, through the end of the evaluation period identified.

Eight flaw evaluation charts were prepared for the region of interest, four for axial flaws, and four for circumferential flaws. The cases covered are listed below:

- Figure 6-13: Maximum Acceptable Initial Axial Flaws, Accounting for PWSCC and Fatigue Crack Growth, with a 10% Inner Diameter Weld Repair, with No PWHT
- Figure 6-14: Maximum Acceptable Initial Axial Flaws, Accounting for PWSCC and Fatigue Crack Growth, with a 10% Inner Diameter Weld Repair, with PWHT
- Figure 6-15: Maximum Acceptable Initial Axial Flaws, Accounting for PWSCC and Fatigue Crack Growth, With a 25% Inner Diameter Weld Repair, with PWHT
- Figure 6-16: Maximum Acceptable Initial Axial Flaws, Accounting for PWSCC and Fatigue Crack Growth, with a 50% Inner Diameter Weld Repair, with PWHT

- Figure 6-17: Maximum Acceptable Initial Circumferential Flaws, Accounting for PWSCC and Fatigue Crack Growth, with a 10% Inner Diameter Weld Repair, with No PWHT
- Figure 6-18: Maximum Acceptable Initial Circumferential Flaws, Accounting for PWSCC and Fatigue Crack Growth, with a 10% Inner Diameter Weld Repair, with PWHT
- Figure 6-19: Maximum Acceptable Initial Circumferential Flaws, Accounting for PWSCC and Fatigue Crack Growth, with a 25% Inner Diameter Weld Repair, with PWHT
- Figure 6-20: Maximum Acceptable Initial Circumferential Flaws, Accounting for PWSCC and Fatigue Crack Growth, with a 50% Inner Diameter Weld Repair, with PWHT

In summary, results show very large flaws are acceptable for service periods up to four years. These results include the required Section XI [1] flaw evaluation margins and were developed for both axial and circumferentially oriented flaws.

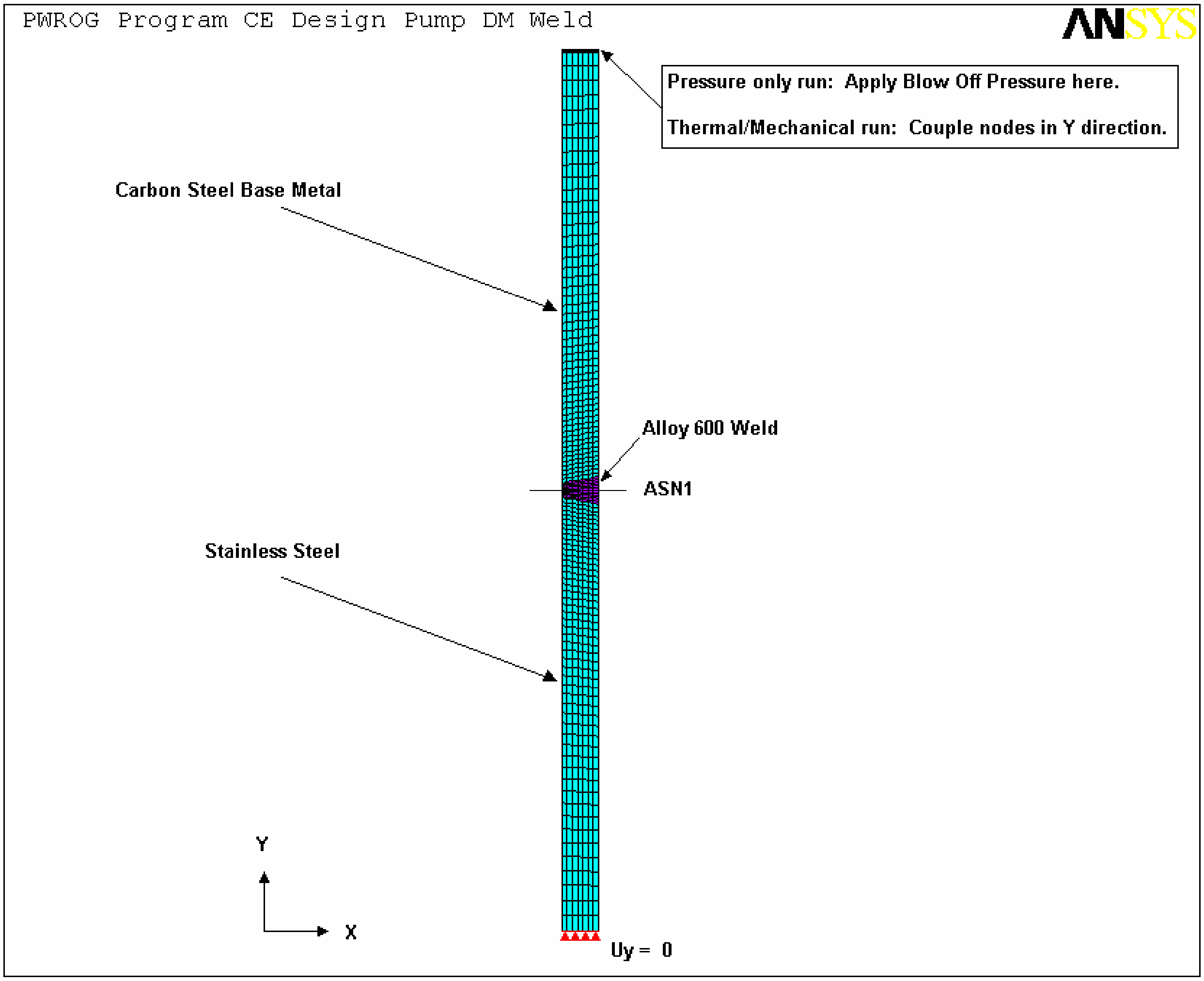

Figure 6-1: Axisymmetric FEA Model for Transient Stress Analysis

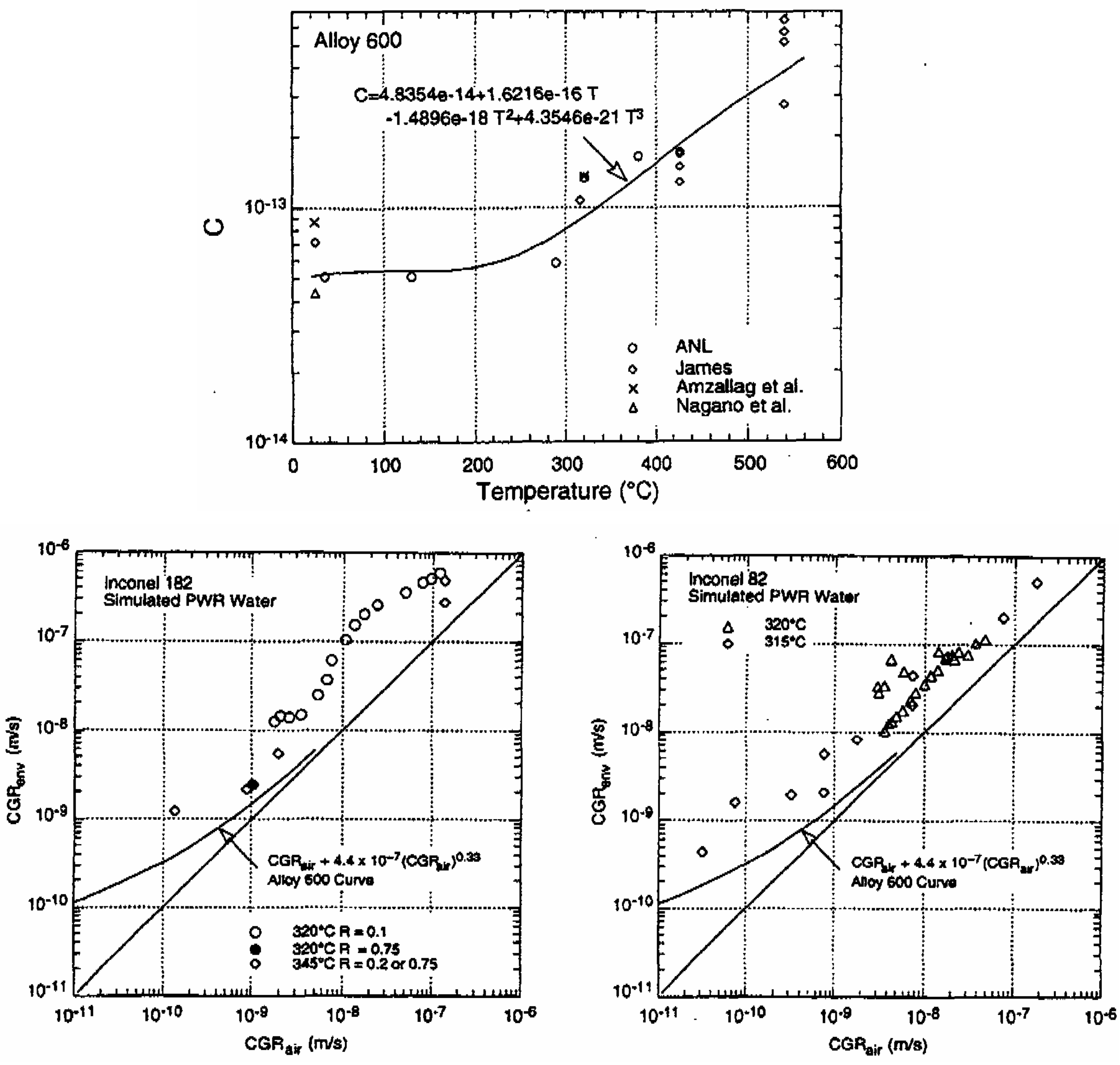

Figure 6-2: Alloy 82/182 Weld Fatigue Crack Growth Rate Properties in a PWR Environment

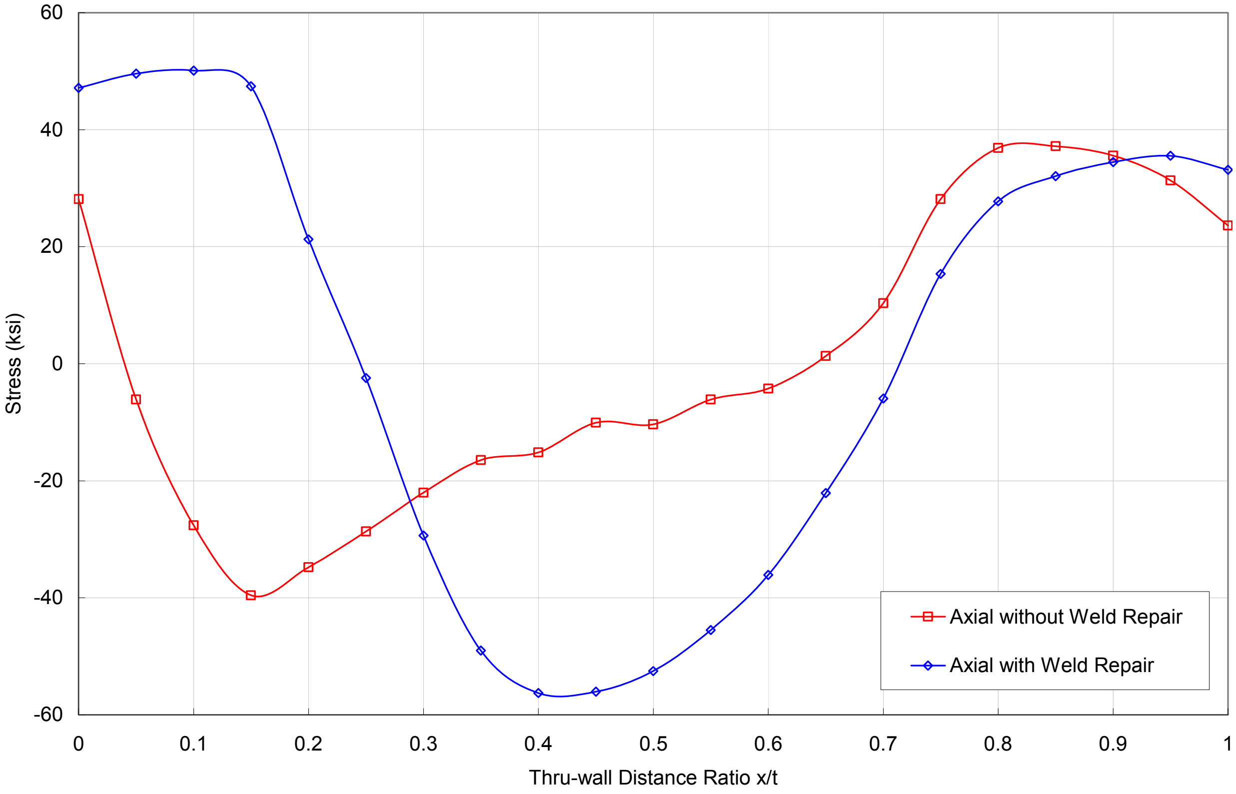

Figure 6-3: Axial Residual Stresses for RCP Suction and Discharge Nozzles [6]

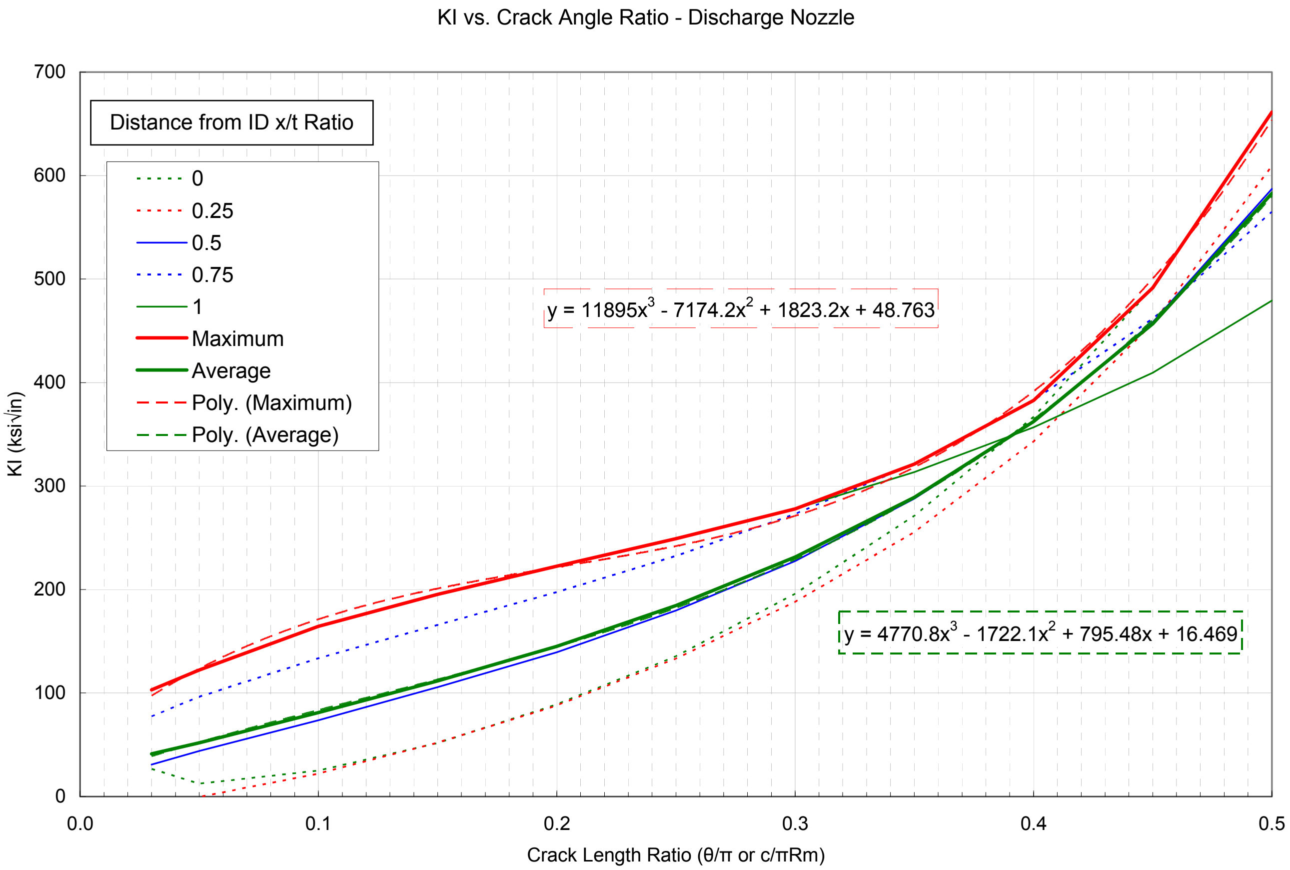

Figure 6-4: Crack Tip Stress Intensity versus Circumferential Through-wall Crack Length Used for PWSCC Growth Evaluation

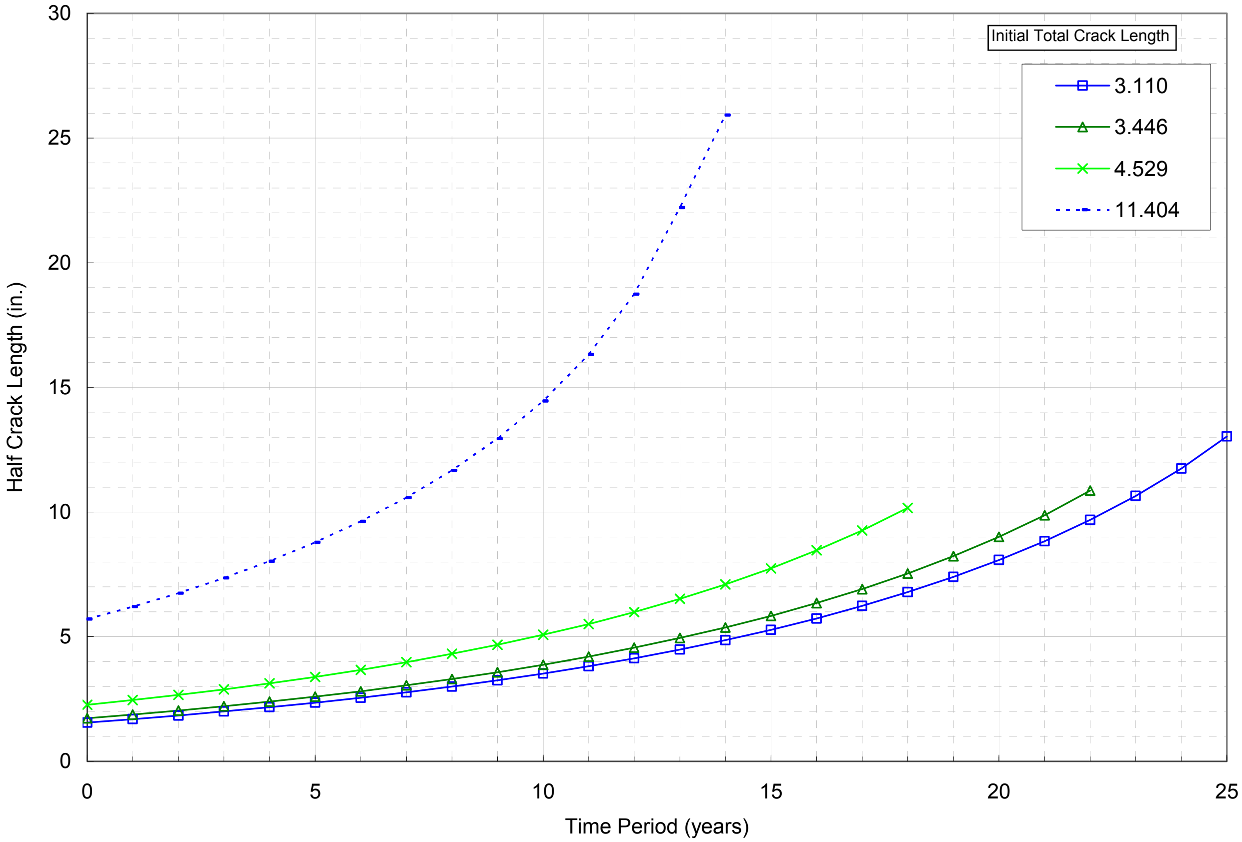

Figure 6-5: PWSCC Only Growth of Circumferential Through-wall Flaws with Maximum Normal Operating Nozzle Axial Loads for Various Initial Lengths

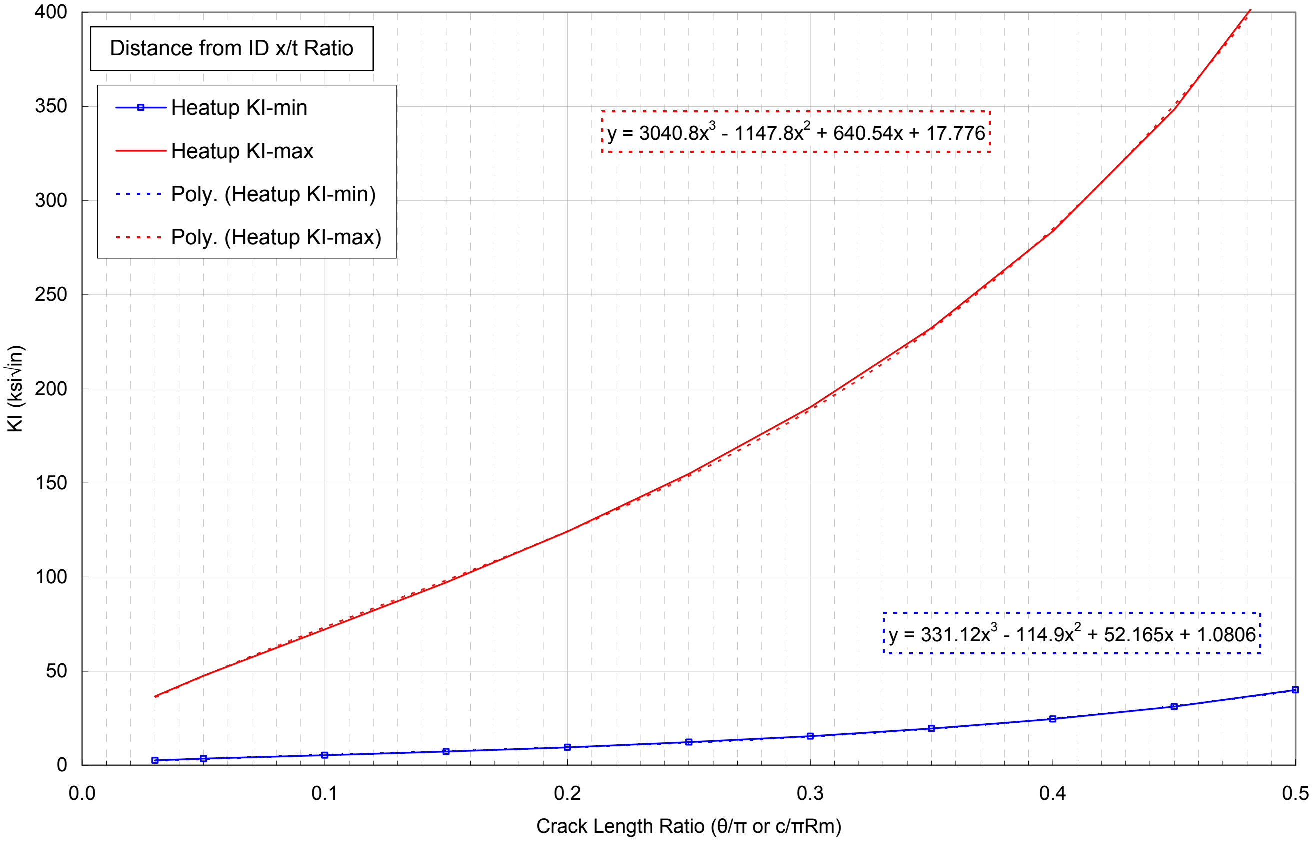

Figure 6-6: Maximum and Minimum Through-wall Crack Tip Stress Intensity Factors during a Heatup Transient as a Function of Circumferential Crack Length

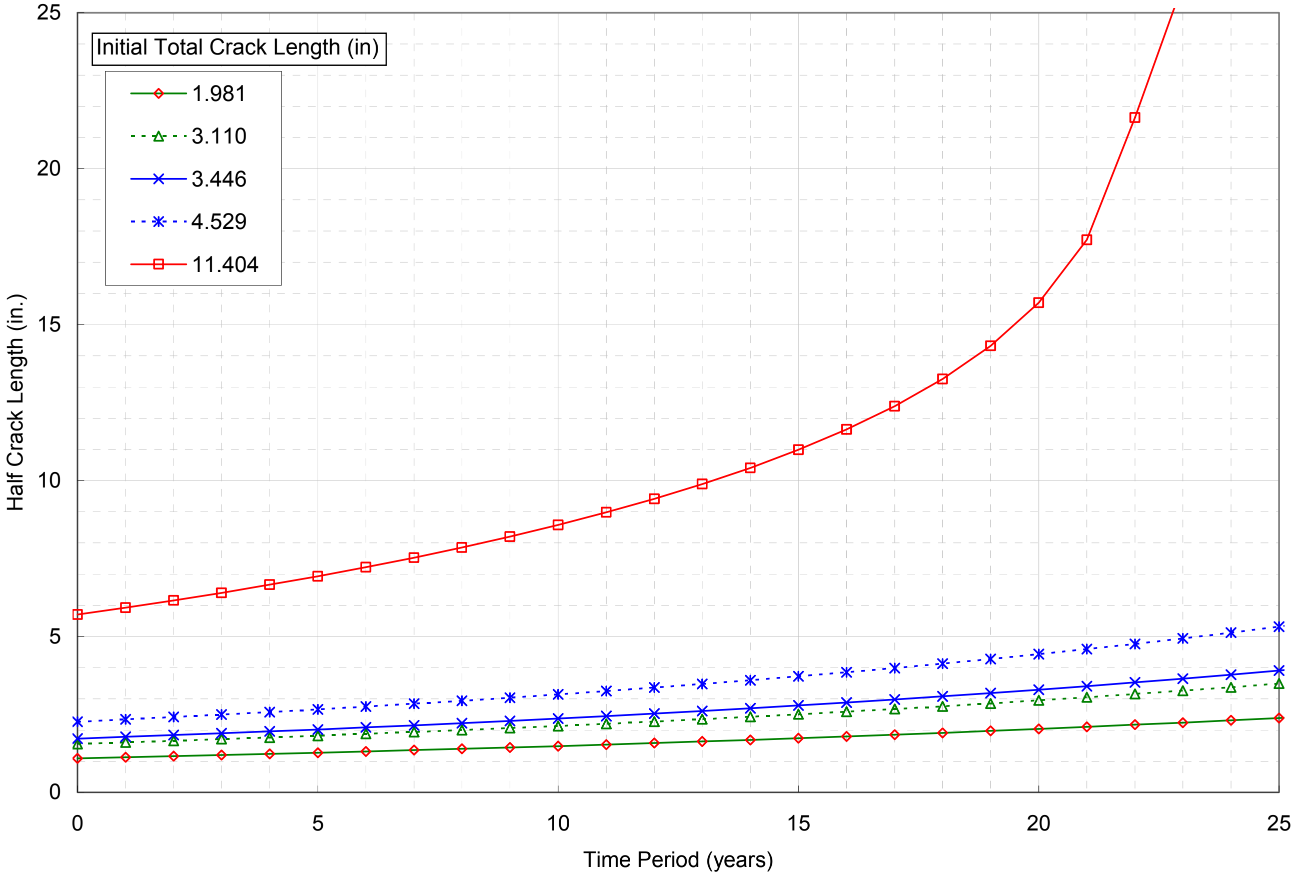

Figure 6-7: Fatigue Only Growth of Circumferential Through-wall Flaws with Maximum Normal Operating Nozzle Axial Loads for Various Initial Lengths

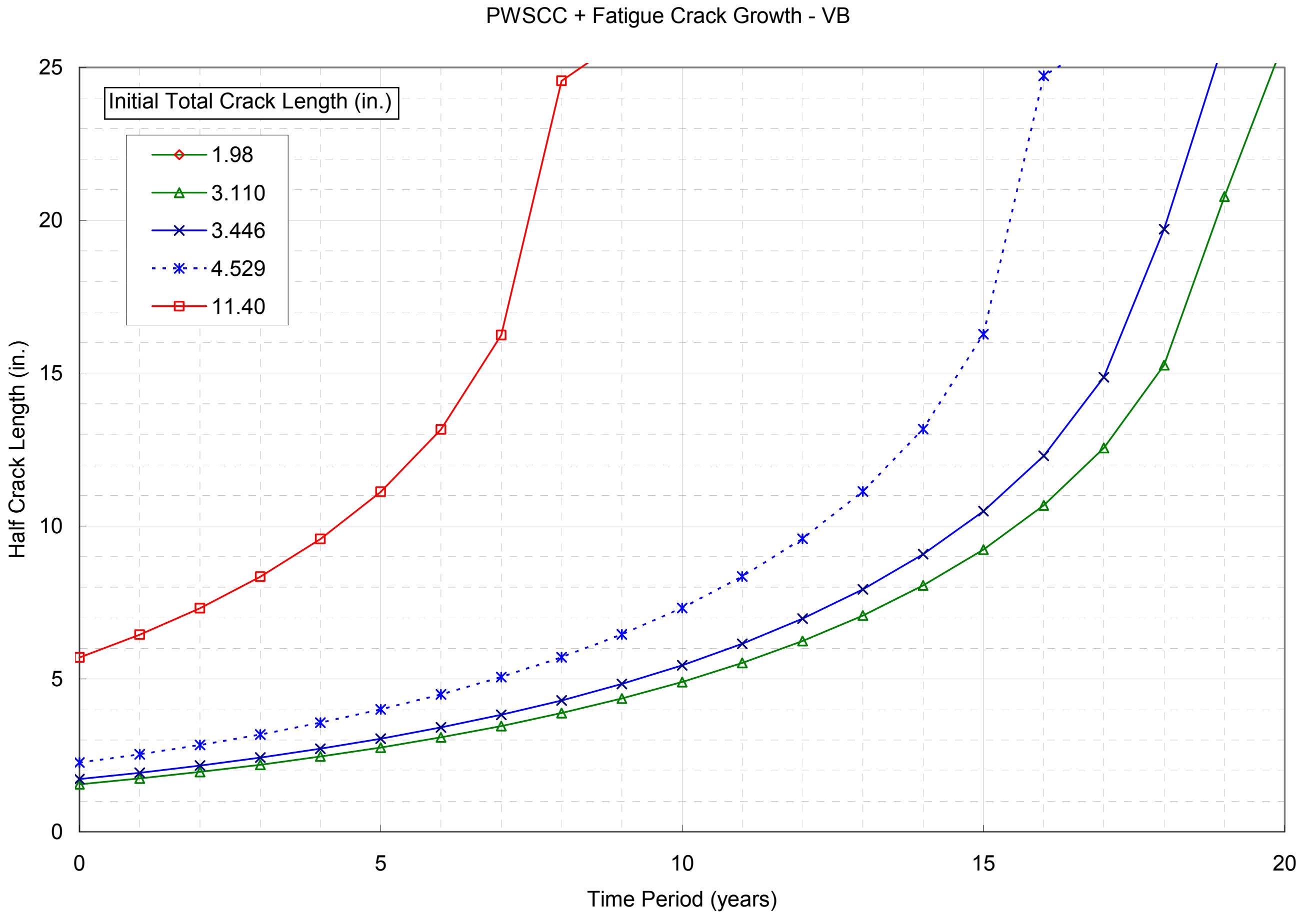

Figure 6-8: Combined PWSCC and Fatigue Growth of Circumferential Through-wall Flaws with Maximum Normal Operating Nozzle Axial Loads for Various Initial Lengths

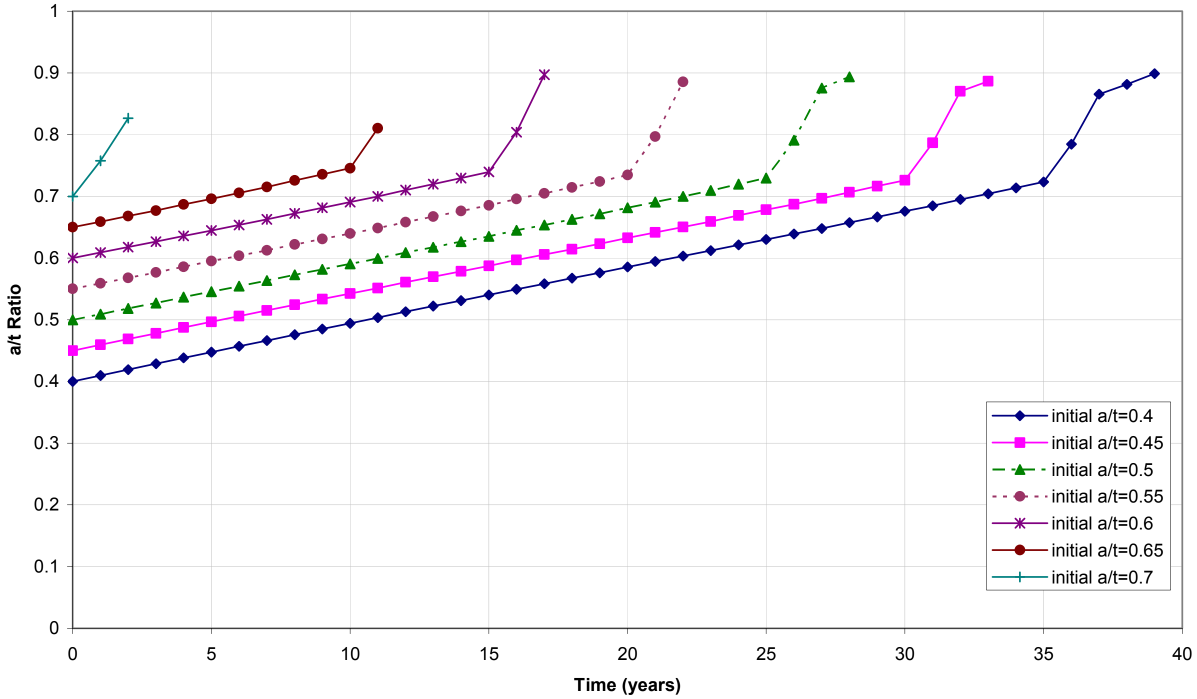

Figure 6-9: Circumferential ID Surface FCG for Maximum Pipe Load with No Residual Stress

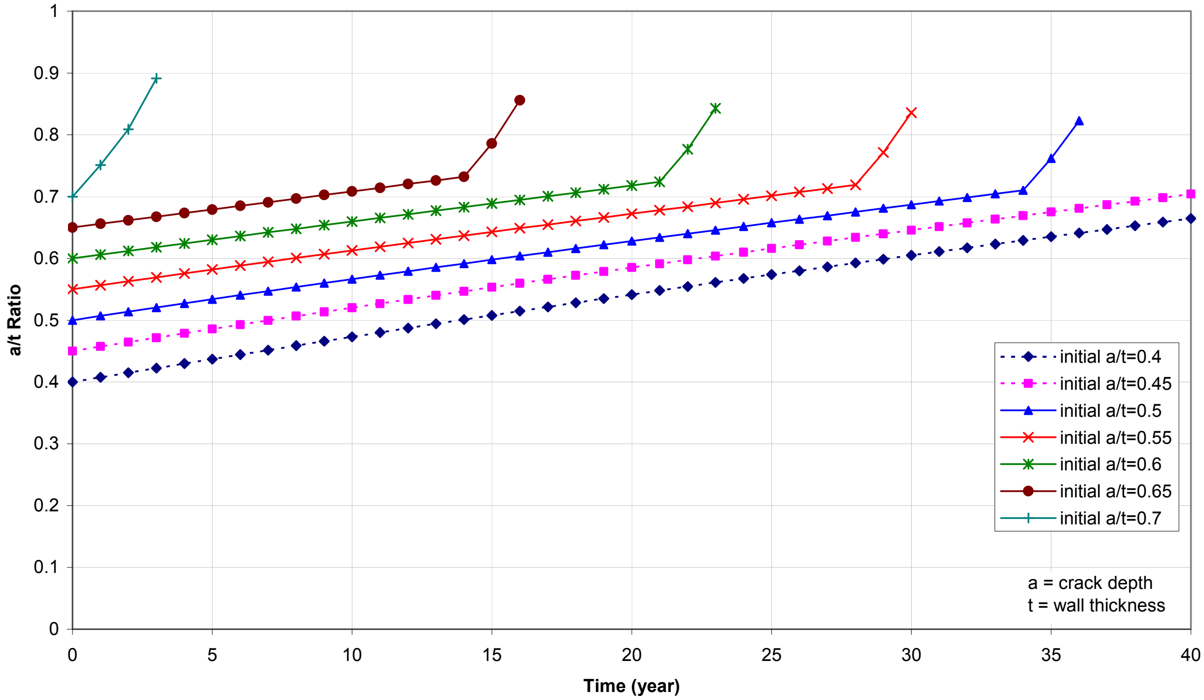

Figure 6-10: Circumferential ID Surface FCG for Minimum Pipe Load with No Residual Stress

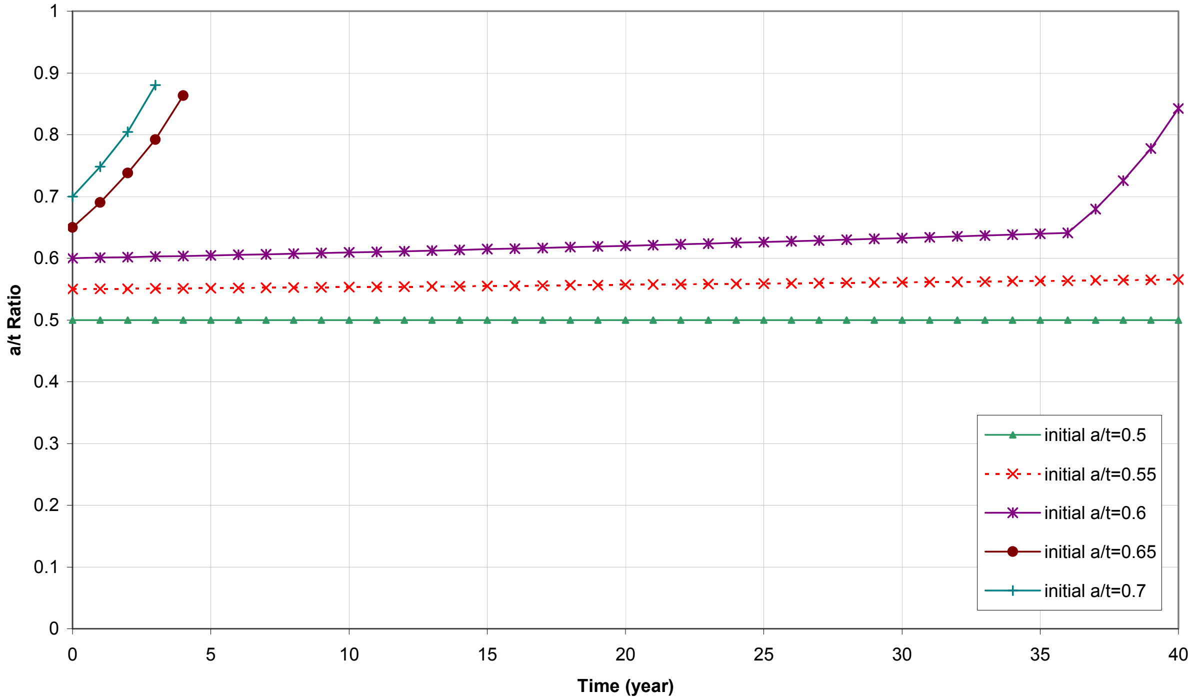

Figure 6-11: Circumferential ID Surface FCG for Maximum Pipe Load with Residual Stress, No ID Repair

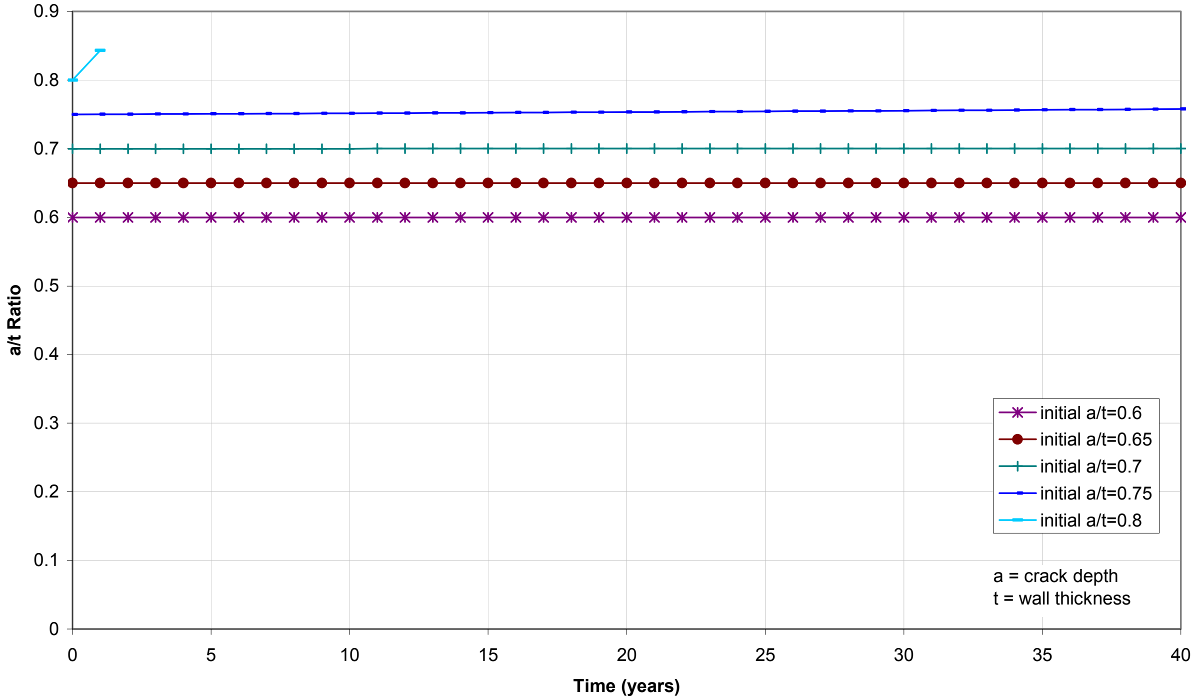

Figure 6-12: Circumferential ID Surface FCG for Minimum Pipe Load with Residual Stress, No ID Repair

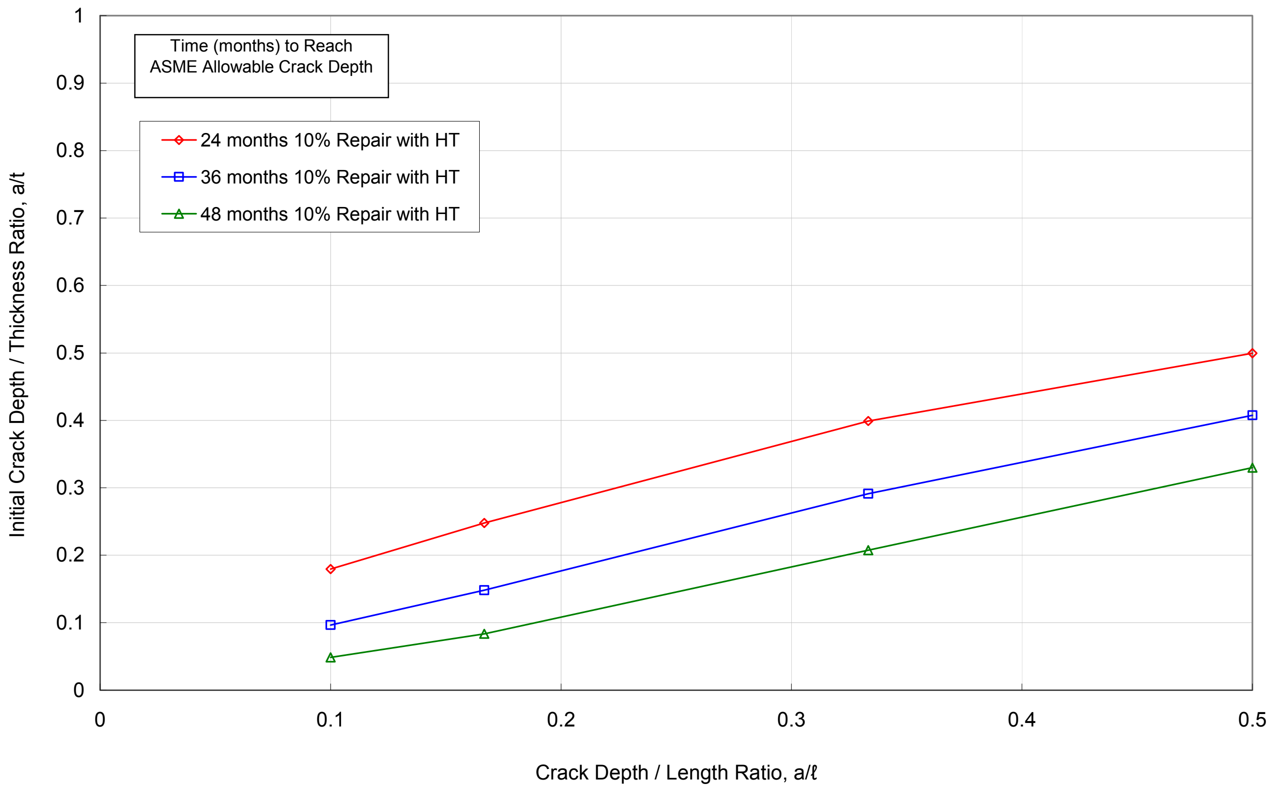

Figure 6-13: Maximum Acceptable Initial Axial Flaws, Accounting for PWSCC and Fatigue Crack Growth, with a 10% Inner Diameter Weld Repair, with No PWHT

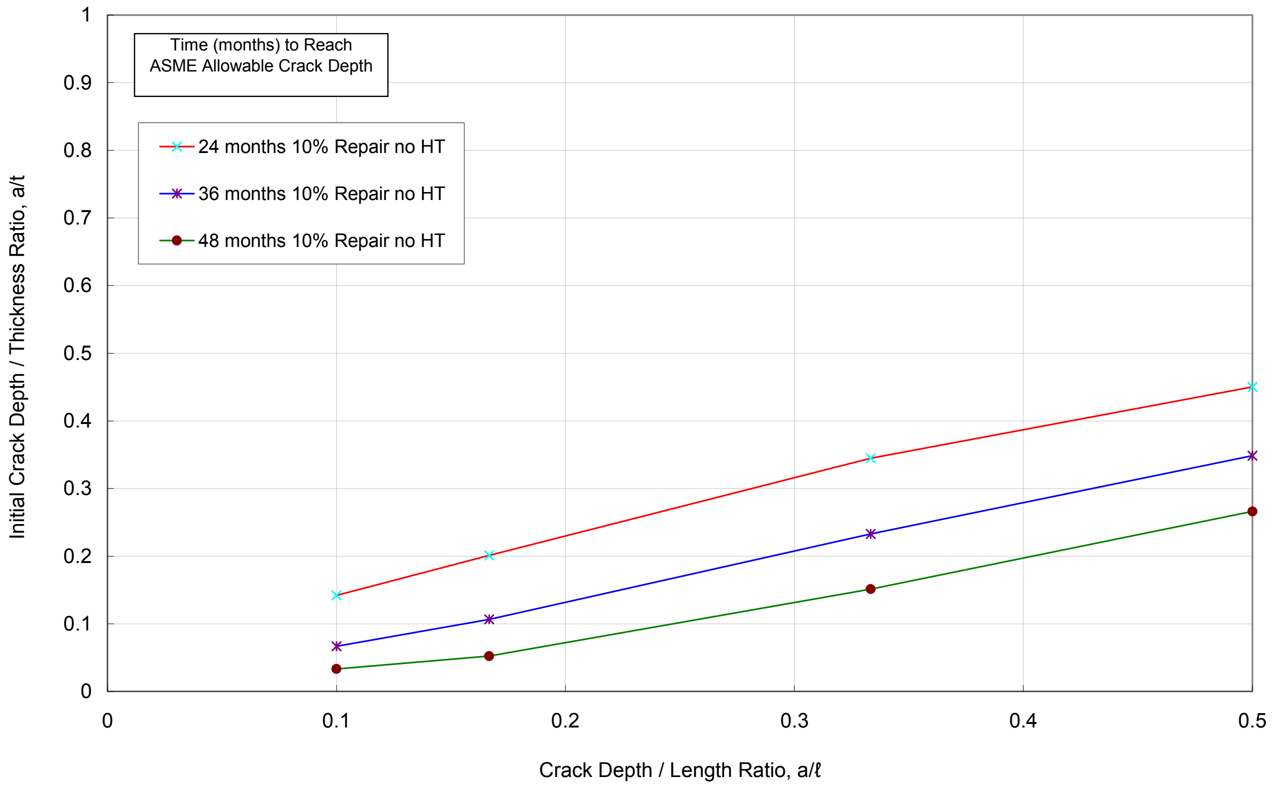

Figure 6-14: Maximum Acceptable Initial Axial Flaws, Accounting for PWSCC and Fatigue Crack Growth, with a 10% Inner Diameter Weld Repair, with PWHT

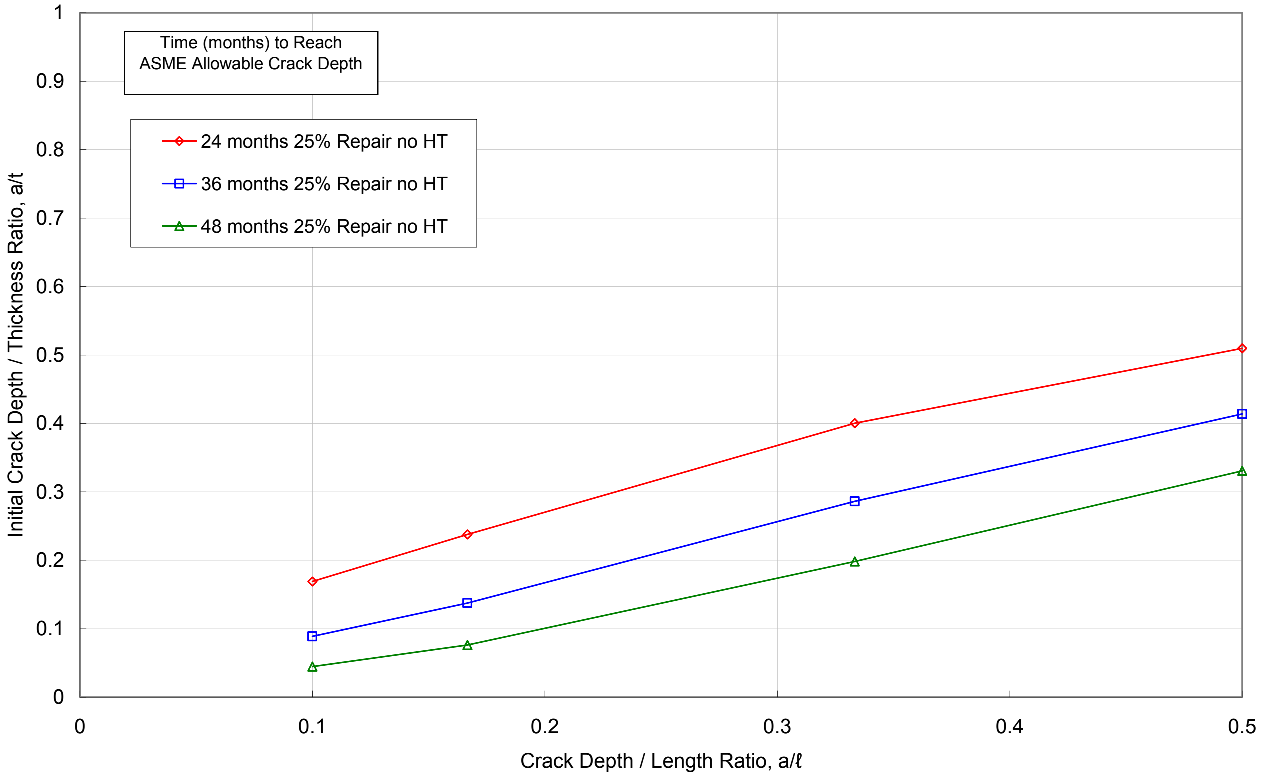

Figure 6-15: Maximum Acceptable Initial Axial Flaws, Accounting for PWSCC and Fatigue Crack Growth, with a 25% Inner Diameter Weld Repair, with PWHT

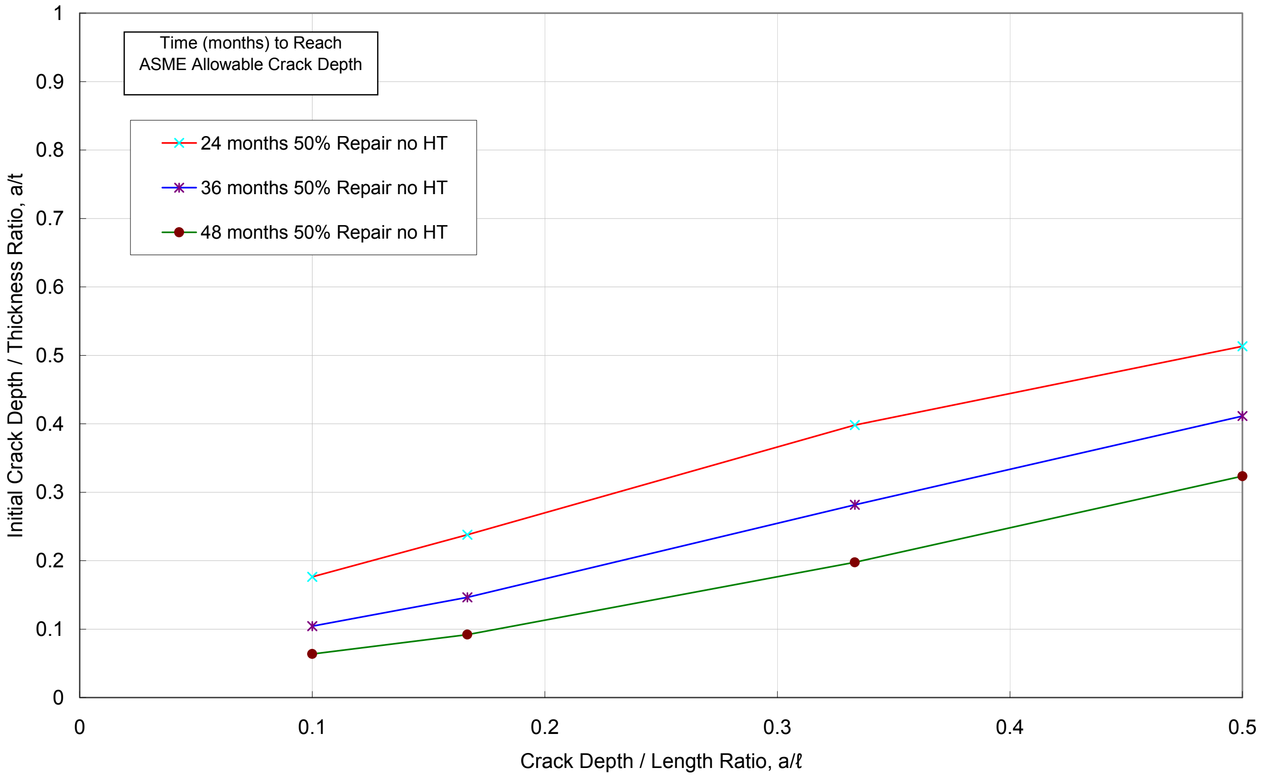

Figure 6-16: Maximum Acceptable Initial Axial Flaws, Accounting for PWSCC and Fatigue Crack Growth, with a 50% Inner Diameter Weld Repair, with PWHT

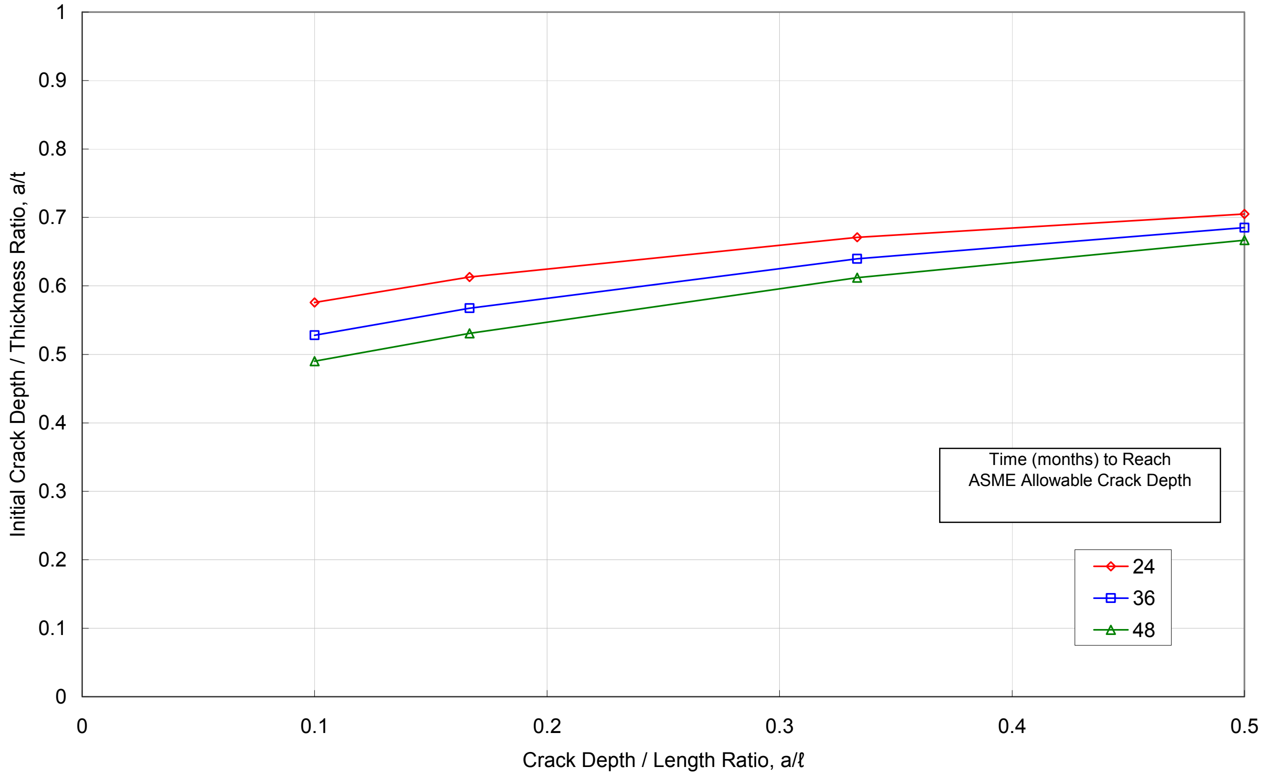

Figure 6-17: Maximum Acceptable Initial Circumferential Flaws, Accounting for PWSCC and Fatigue Crack Growth, with a 10% Inner Diameter Weld Repair, with No PWHT

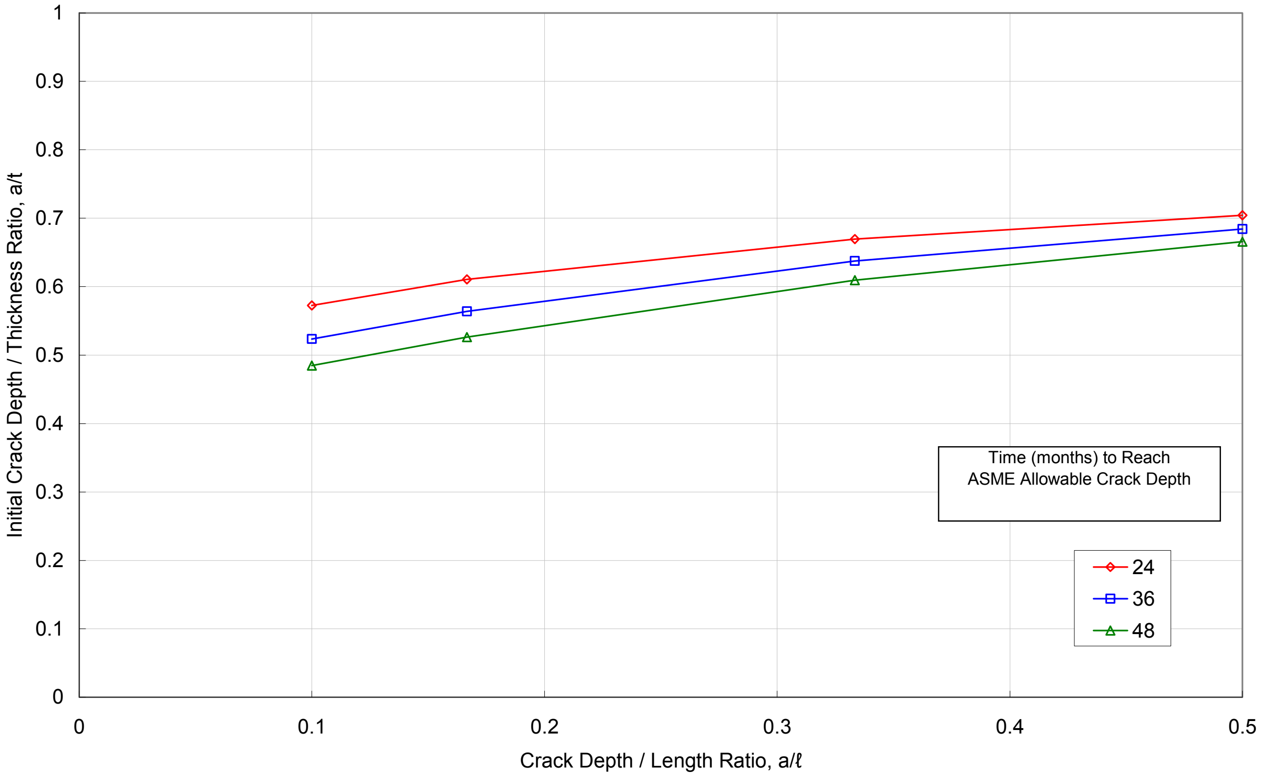

Figure 6-18: Maximum Acceptable Initial Circumferential Flaws, Accounting for PWSCC and Fatigue Crack Growth, with a 10% Inner Diameter Weld Repair, with PWHT

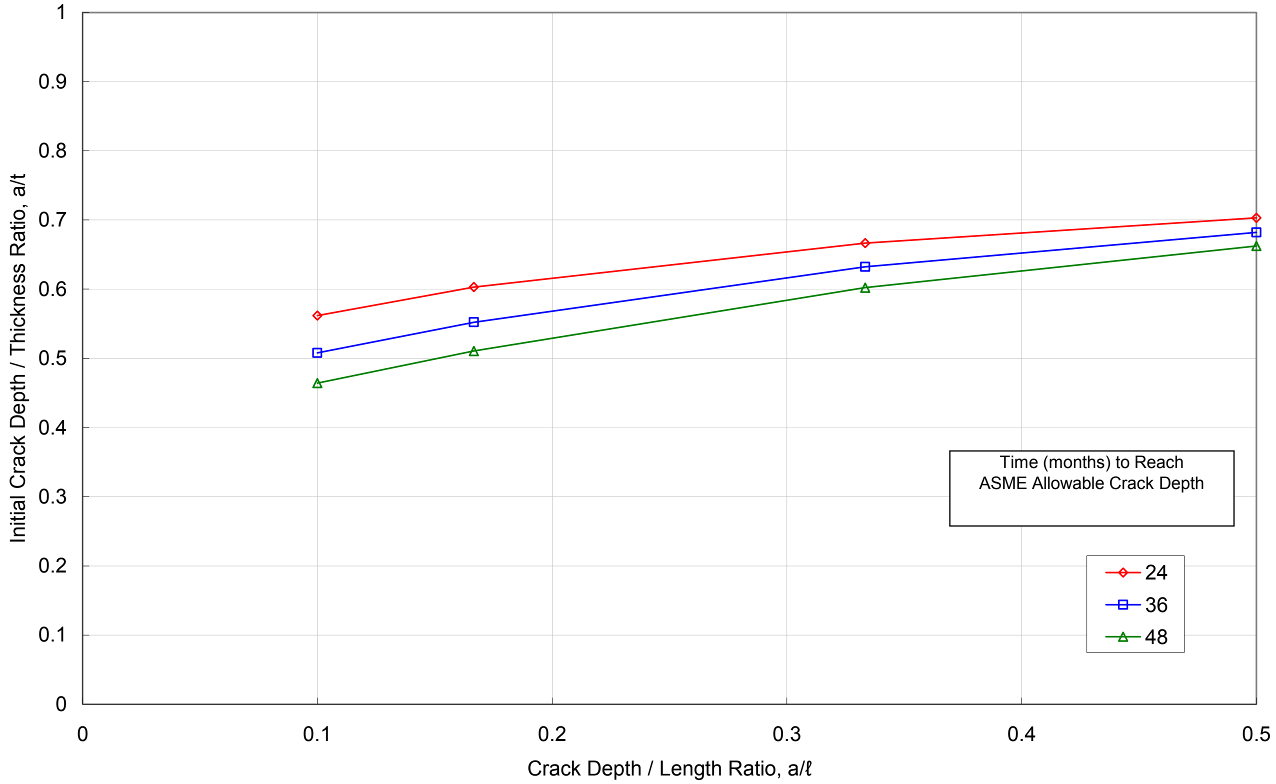

Figure 6-19: Maximum Acceptable Initial Circumferential Flaws, Accounting for PWSCC and Fatigue Crack Growth, with a 25% Inner Diameter Weld Repair, with PWHT

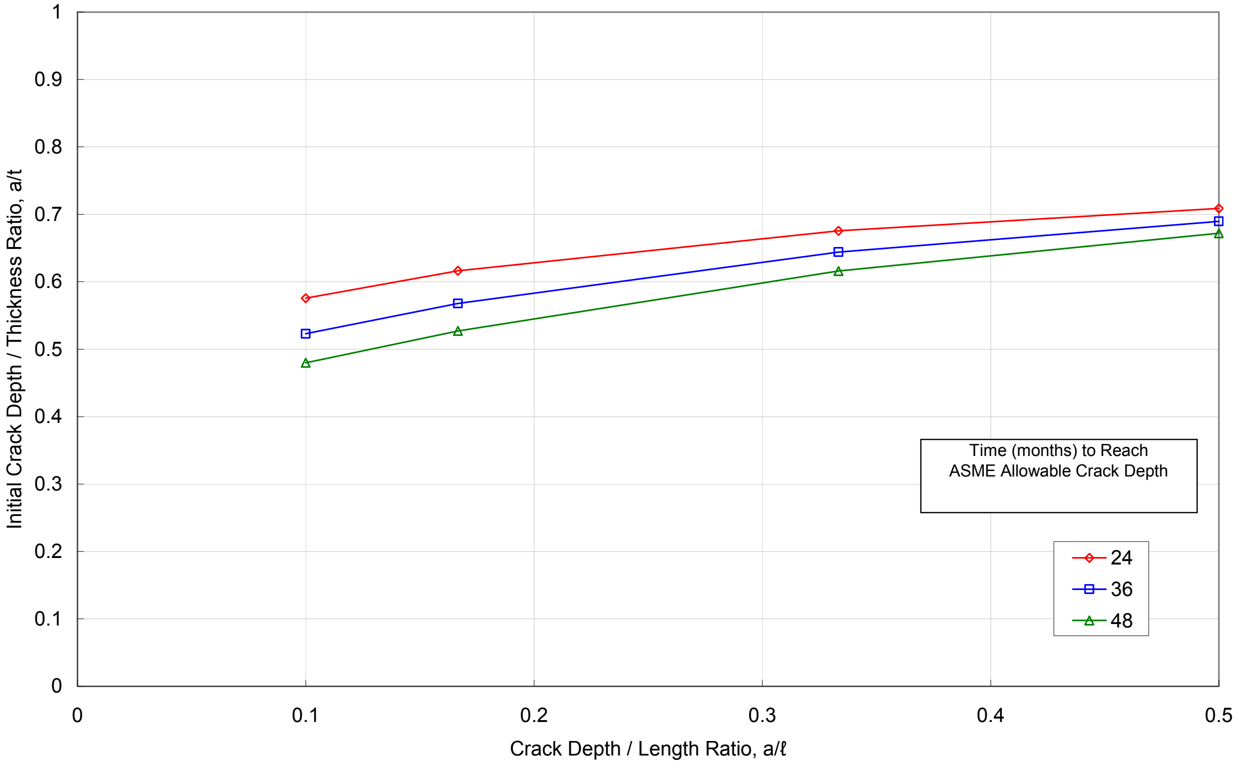

Figure 6-20: Maximum Acceptable Initial Circumferential Flaws, Accounting for PWSCC and Fatigue Crack Growth, with a 50% Inner Diameter Weld Repair, with PWHT

7 ADVANCED PWSCC GROWTH BY FEA

Flaw evaluations of CE design RCP outlet nozzle Alloy 82/182 dissimilar metal butt welds were also performed using a rigorous three-dimensional finite element model containing a circumferential flaw. Both, finite depth and length inside surface circumferential flaws, as well as through-wall flaws, were considered in the evaluation. The purpose of the inside surface flaws was to assess the time period for the flaw to grow to an acceptable depth per Section XI [1], and also to grow through the wall and reach the outside surface. The through-wall circumferential case was to compute the time period required for a maximum obstruction flaw length to grow in the circumferential direction and reach a critical flaw length. Only the PWSCC growth mechanism was considered in this three-dimensional finite element analysis (FEA) flaw evaluation. In all the evaluations, the goal was to generate a realistic crack growth assessment, for comparison with the traditional methods used elsewhere in the project, and reported in Sections 5 and 6.

7.1 INITIAL FLAW SIZE

The initial inside surface finite depth flaw lengths considered in this evaluation are a 14% and 23% of circumference of the nozzle. The 14% flaw represents, conservatively, the largest single obstruction from the charging or spray nozzle and accounts for the inspection transducer width on either side of the nozzle. Surface flaw depths of 20% and 30% were assumed. These depths were chosen based on very conservative aspect ratios of 0.04 and 0.03, respectively. These are significantly larger than the aspect ratio of 0.1667 observed in service experience, and it is highly likely that any flaws deeper than this would have tails which would be detected in the inspected region. Since the finite element analysis software does not allow surface flaws to grow to through-wall as a continuous crack growth process due to mesh changing restrictions, the surface flaw was first allowed to grow through the wall and almost reach the outside surface with depths exceeding 90% of the wall thickness. Then, the flaw was assumed to be through the wall.

Subsequent three-dimensional FEA evaluations consisted of a through-wall flaw with different inside and outside lengths that simulated the end of surface flaw growth, which was then allowed to propagate around the circumference to reach the critical flaw length. Total service life was then obtained by addition of the time periods from the ID surface flaw to reach the outside surface and then propagate in the circumferential direction.

7.2 STRESS INTENSITY FACTOR CALCULATION

SIF calculations in the FEACrack software program are performed by using crack tip finite elements and strain-energy contour integrals around the crack front. The fracture mechanics model geometry is generated using FEACrack. The five different cases completed are listed in Table 7-1. The model geometry, model external loads, and initial flaw sizes are defined in FEACrack software input parameters. Using this information, the software generates three-dimensional FEA models with surface or through-wall cracks for crack growth with a continuously moving crack front and prepares an input mesh to ANSYS for the finite element solution.

Once the FEA model with flaws is analyzed by ANSYS, the FEACrack program processes the results for crack tip SIFs along the crack front. The SIFs are obtained using linear elastic J-integral and K_I relationships.

Initial surface flaw depths considered a range between 20% and 30% of the wall thickness. This will address the range in depth of the ID flaws that may have been missed during an in-service inspection. These initial flaw depths were analyzed to determine the time period for the flaw to reach the allowable depth per Section XI [1], and then to penetrate the nozzle wall. A semi-elliptical surface flaw in the circumferential direction was assumed for the crack front profile and allowed to grow based on the crack front K_I values. The four surface flaw cases were:

1. 14% length 20% depth inside surface circumferential flaw,
2. 14% length, 30% depth inside surface circumferential flaw,
3. 23% length 20% depth inside surface circumferential flaw, and
4. 23% length, 30% depth inside surface circumferential flaw.

The fifth flaw considered in this analysis was a through-wall flaw with an initial flaw length of 14% of the nozzle circumference, resembling the shape of the last step of the flaw shape from flaw Case 2, mentioned above. Details of the flaw depths and lengths are listed in Table 7-1.

7.3 FINITE ELEMENT FRACTURE MECHANICS MODEL

FEACrack was used to generate all the finite element fracture mechanics models analyzed. A typical FEA model is shown in Figure 7-1. All surface flaw cases evaluated in this study were based on the same set of parameters, for ANSYS eight-noded solid element type SOLID45. The FEA mesh parameters for the through-wall case vary slightly from those of the surface flaw cases to accommodate the differences in the flaw shapes. An appropriate axial length of the piping was included in the model to minimize the boundary effects on the dissimilar metal weld location.

7.4 BOUNDARY CONDITIONS

Each FEA model developed has a quarter-symmetry with the center of the dissimilar metal weld taken as a symmetry plane and the other one along the nozzle axis. The boundary conditions prescribed on the symmetry planes are shown in Figure 7-2. The DM weld crack symmetry plane is fixed along the axial x-direction of the nozzle. The nozzle axial symmetry plane has a fixed boundary condition along the circumferential z-direction. These boundary conditions are automatically assigned within FEACrack by specifying a quarter symmetric pipe model. FEACrack automatically applies a fixed boundary condition at an appropriate node in the y-direction to prevent rigid body motion.

Fabrication welding residual stresses from MRP-113 [6] show the large diameter pipes typical of the CE fleet cold leg nozzles are compressive in nature in the 15% to 40% through-wall distance from the inside surface. As the magnitude of this compressive residual stress is high, in the range of 20 to 50 ksi, any crack growth in the radial direction in the FEACrack program is prevented, and the crack propagation stops. Since the intent of this study on the propagation of inside surface cracks is to determine the time period to reach through-wall thickness, fabrication residual stresses were ignored. Only the crack face pressure of 2.5 ksi due to internal pressure loads were applied. The initial fabrication residual stresses were also ignored for the through-wall Case 3, for consistency.

7.5 NOZZLE END AXIAL LOADS

An axial force and bending moment loading on the nozzle free-end surface were applied in the FEACrack model as shown in Figure 7-3 and Figure 7-4. These loadings were applied to the FEA models through the element face pressures. Based on the free-end surface element orientation, element face pressures are automatically calculated by FEACrack and applied to the appropriate elements.

7.6 PWSCC CRACK GROWTH WITH FEACRACK PROGRAM

All evaluation cases considered in this study are summarized in Table 7-1. Figure 7-5, Figure 7-7, Figure 7-9, Figure 7-11, and Figure 7-13 show the crack front shape plots for each case as a function of time. As the fabrication weld residual stresses were ignored due to their compressive nature near the ID surface, the crack front shapes maintain their shape close to the initial elliptical shape. In all the surface flaw cases, the crack fronts grow significantly in the radial direction with minimal growth occurring in the circumferential direction. The presence of residual stress may change this trend, but for deeper cracks only, as the shallower ones have compressive residual stresses.

The total amount of time to reach the critical flaw size is determined by adding the amount of time shown for an internal surface flaw to reach through-wall and the amount of time for the through-wall crack to reach the critical flaw size.

According to Cases 1 and 3, the amount of time it takes for an internal surface flaw with a length equal to 14% of the circumference and depth equal to 20% of the wall to reach through the thickness is 12.5 years (Case 1). An additional 8.5 years is required for the flaw to grow circumferentially to reach the critical crack length (Case 3) with total time equaling 21 years. Times for various initial flaw sizes can be inferred from Figure 7-5 and Figure 7-7.

An inside surface flaw with 23% circumferential length and 20% through the wall depth, shown in Figure 7-11, takes approximately 11 years to reach through-wall. Once this flaw reaches the outside surface, the resulting through-wall flaw propagates circumferentially to reach the critical flaw length within a very short time, so the total time to critical length is about equal to the time to penetrate the wall.

Crack tip stress intensity factors are plotted in Figure 7-6, Figure 7-8, Figure 7-10, Figure 7-12, and Figure 7-14 for Cases 1 through 5, respectively. These plots show a variation of SIFs during the crack growth period at various time steps. Trends in these plots show the SIFs are low near the ID surface, and hence causes very slow growth along the circumferential direction. For the through-wall Case 3 shown in Figure 7-10, the SIF distribution is high at the ID surface, due to the flaw shape assumption and quickly evens out, indicating that the flaw shape will approach radial through-wall shape and then grows more uniformly. This is seen by the approximately parallel crack fronts in Figure 7-9. All the FEACrack analyses assumed crack growth based on local SIFs.

Table 7-1: Initial Flaw Dimensions for Three-Dimensional FEA PWSCC Analyses

Case	Flaw Length (% Circumference)	Flaw Depth (% Wall Thickness)	Length (in)	Depth (in)
1	14	20	13.2	0.6
2	14	30	13.2	0.9
3	14	Through-wall	14.5	Through-wall
4	23	20	21.7	0.6
5	23	30	21.7	0.9

Notes:

All three-dimensional FEAs were performed with RCP discharge nozzle geometry with a nominal pipe geometry having an inside radius of 15 inches and a wall thickness of 3 inches.

The through-wall flaw length on the inside surface for Case 3 was assumed to be the same as that at the end of the flaw growth for surface flaw Case 2.

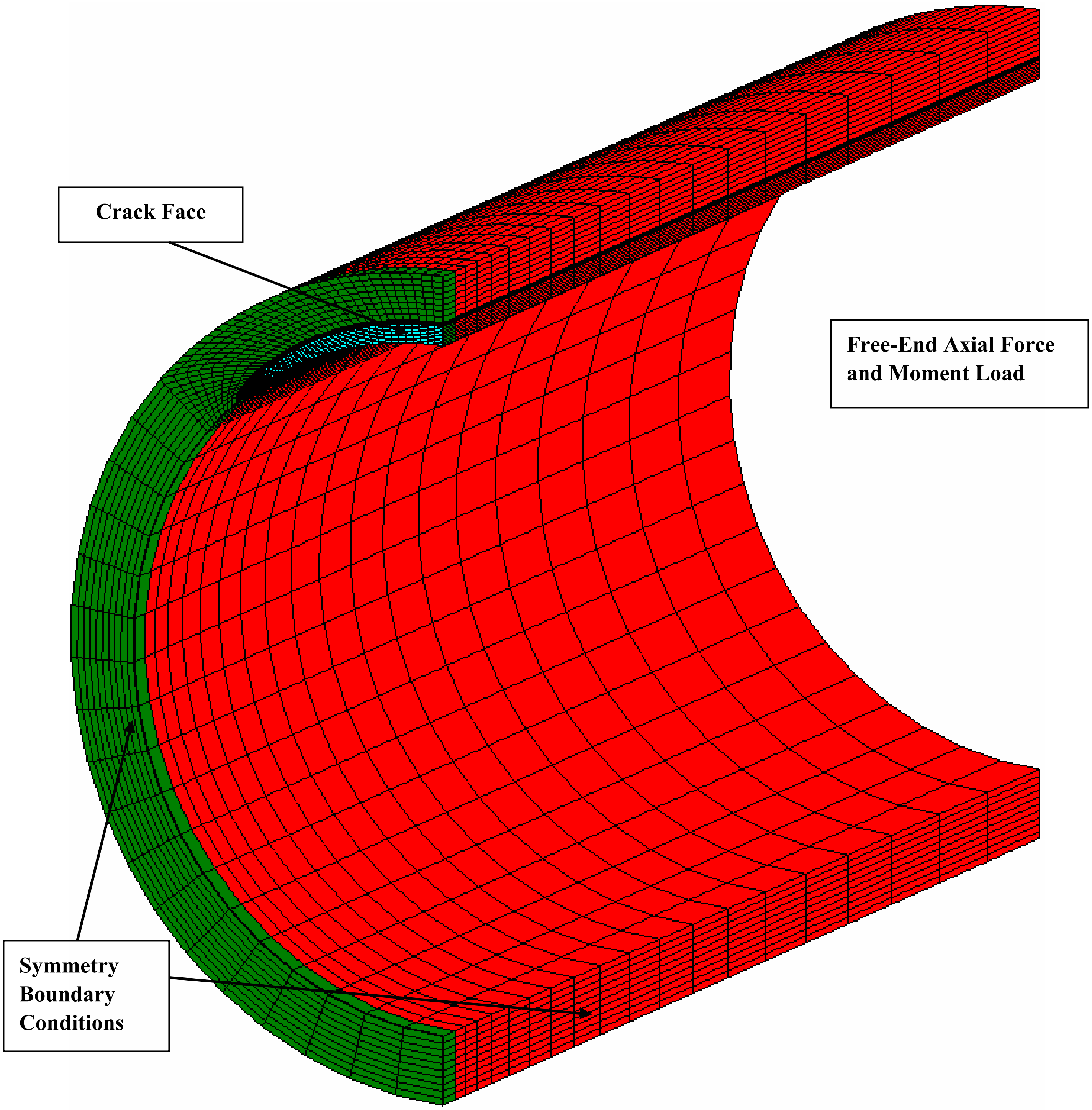

Figure 7-1: Finite Element Fracture Mechanics Model

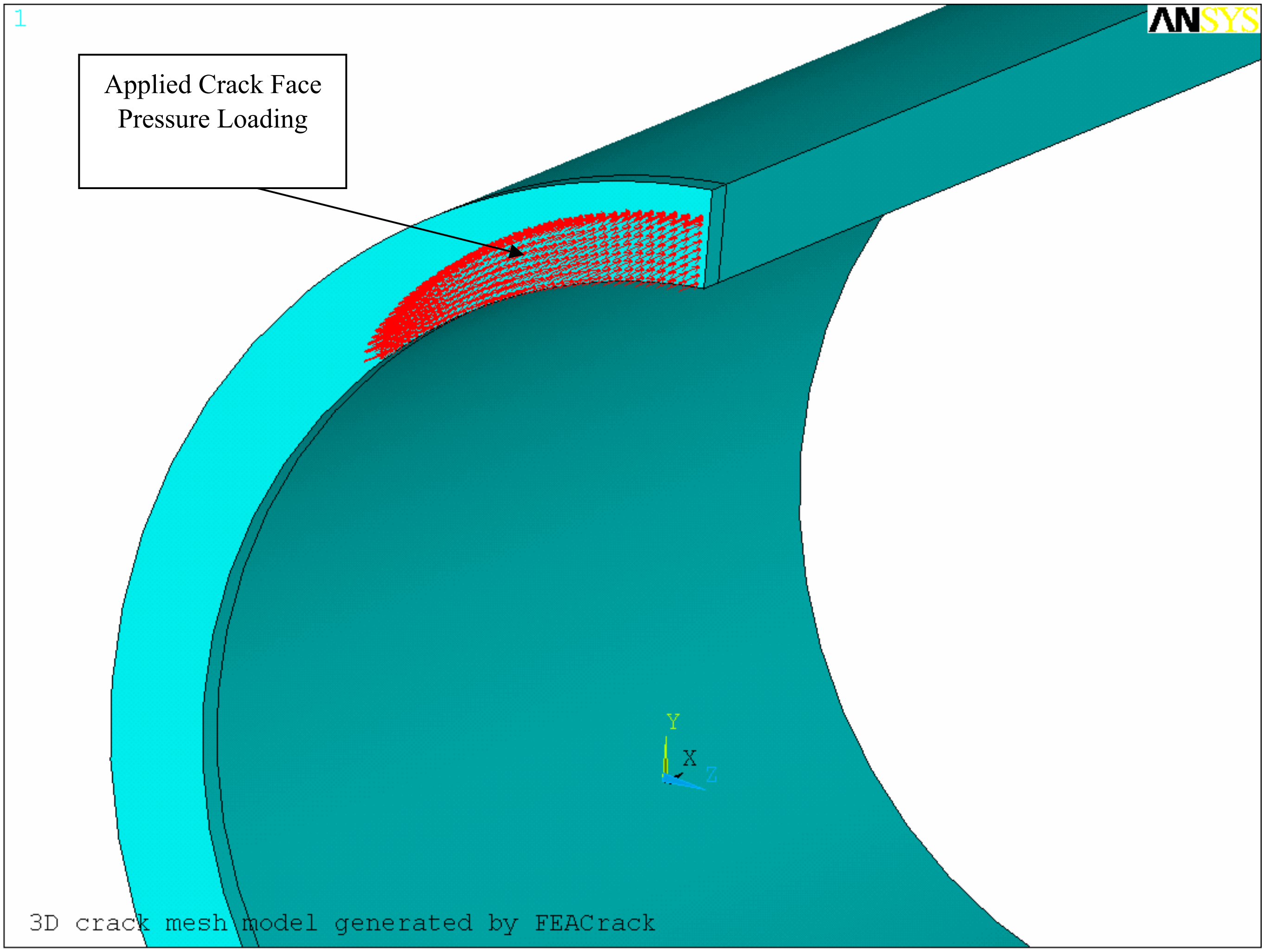

Figure 7-2: Crack-face End View of Applied Crack Face Pressures

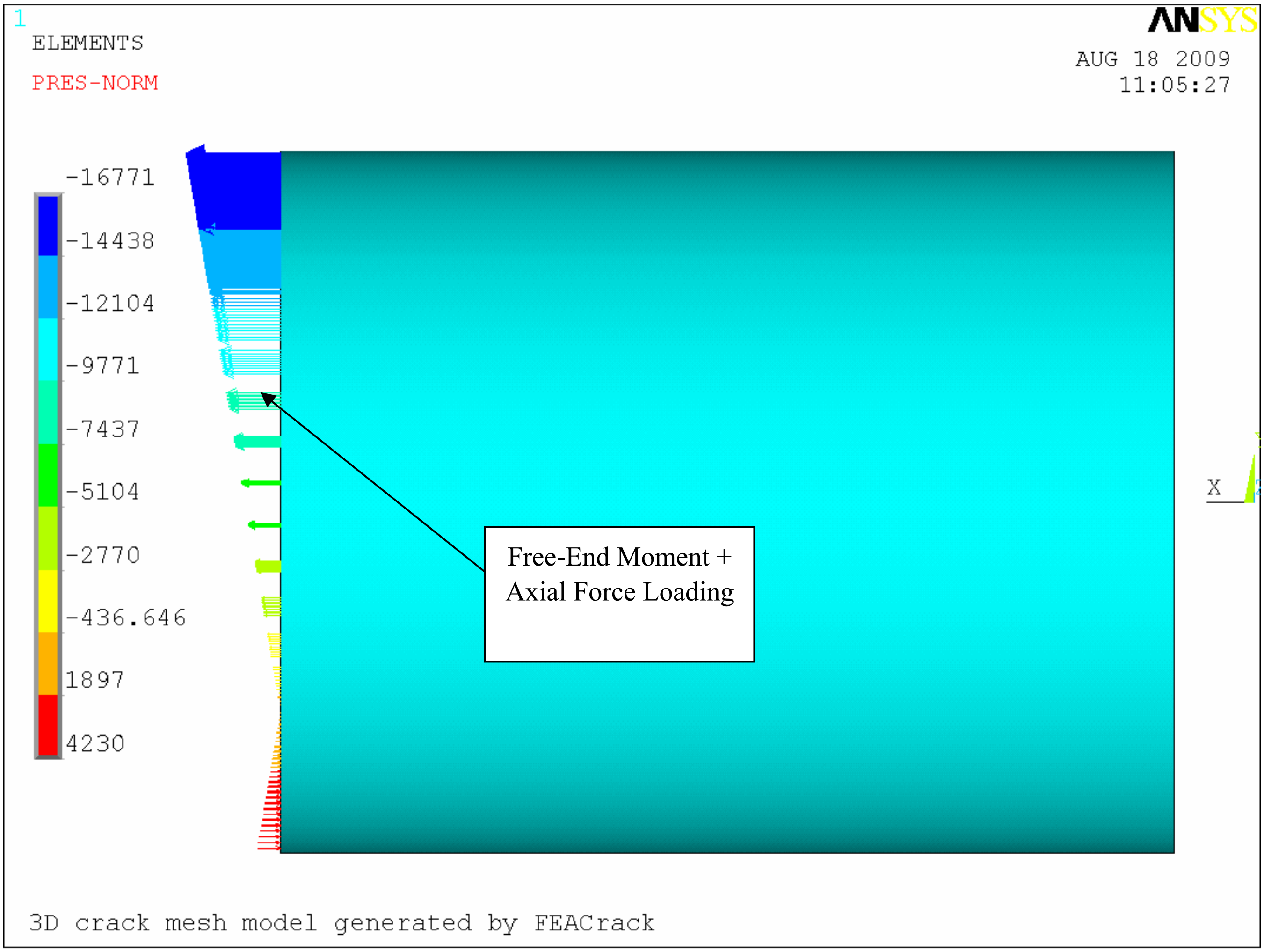

Figure 7-3: Applied Free-end Pressures (for Moment plus Axial Force)

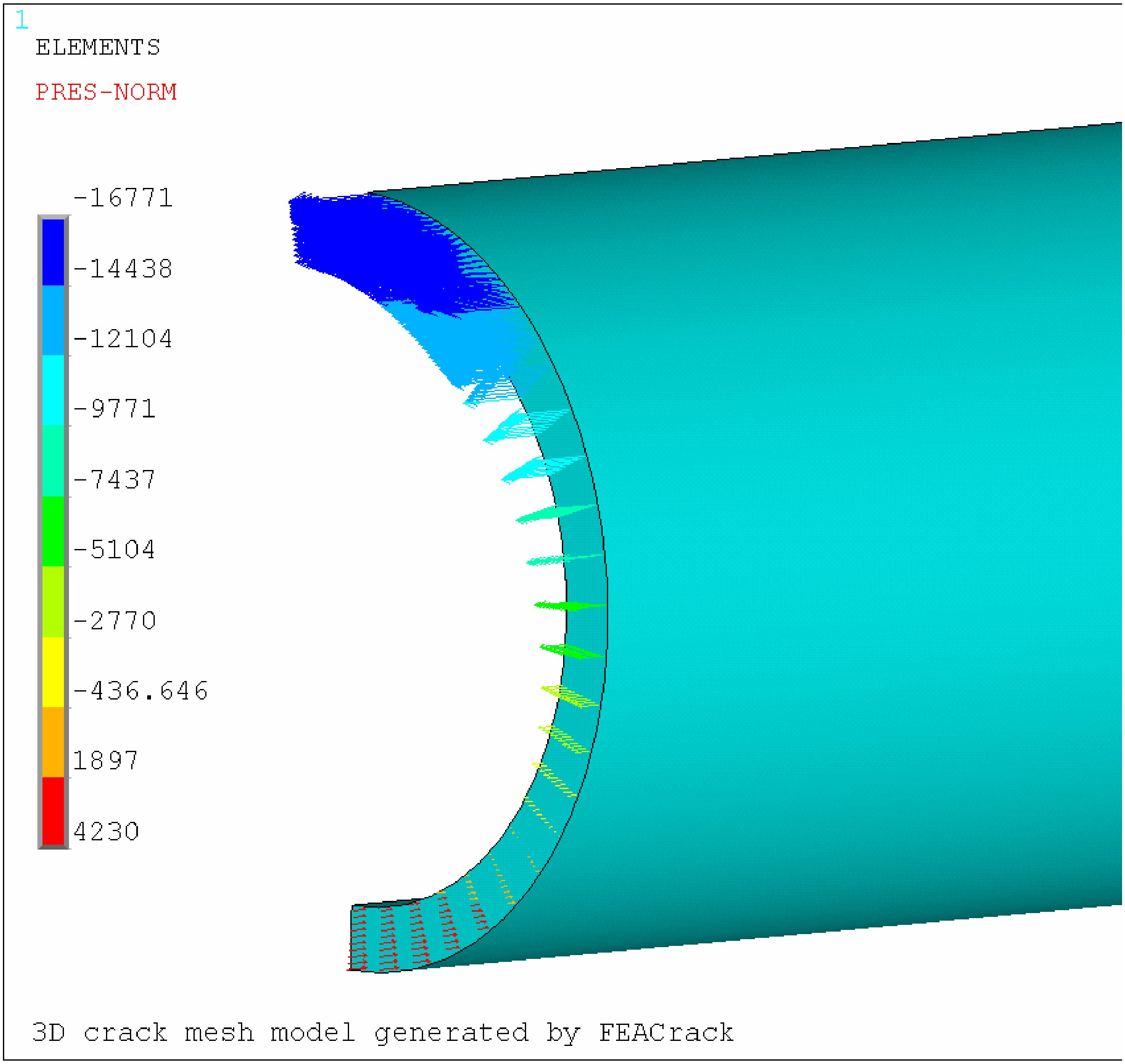

Figure 7-4: Rotated View of Applied Free-end Pressures (for Moment plus Axial Force)

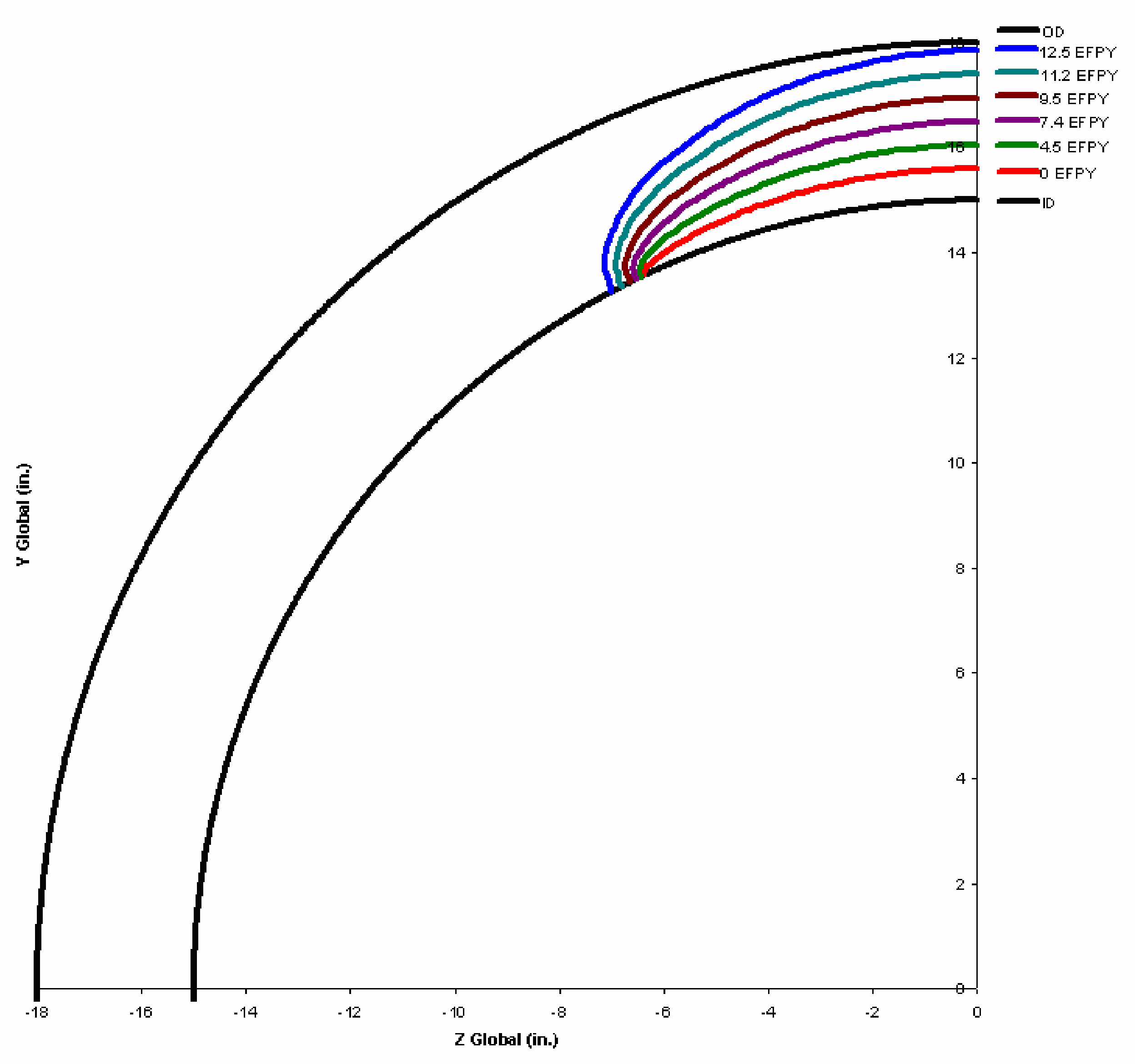

Figure 7-5: PWSCC Flaw Growth with Initial ID Surface Flaw of 14% Circumferential, 20% Depth, Case 1

Note: EFPY = Effective Full Power Years

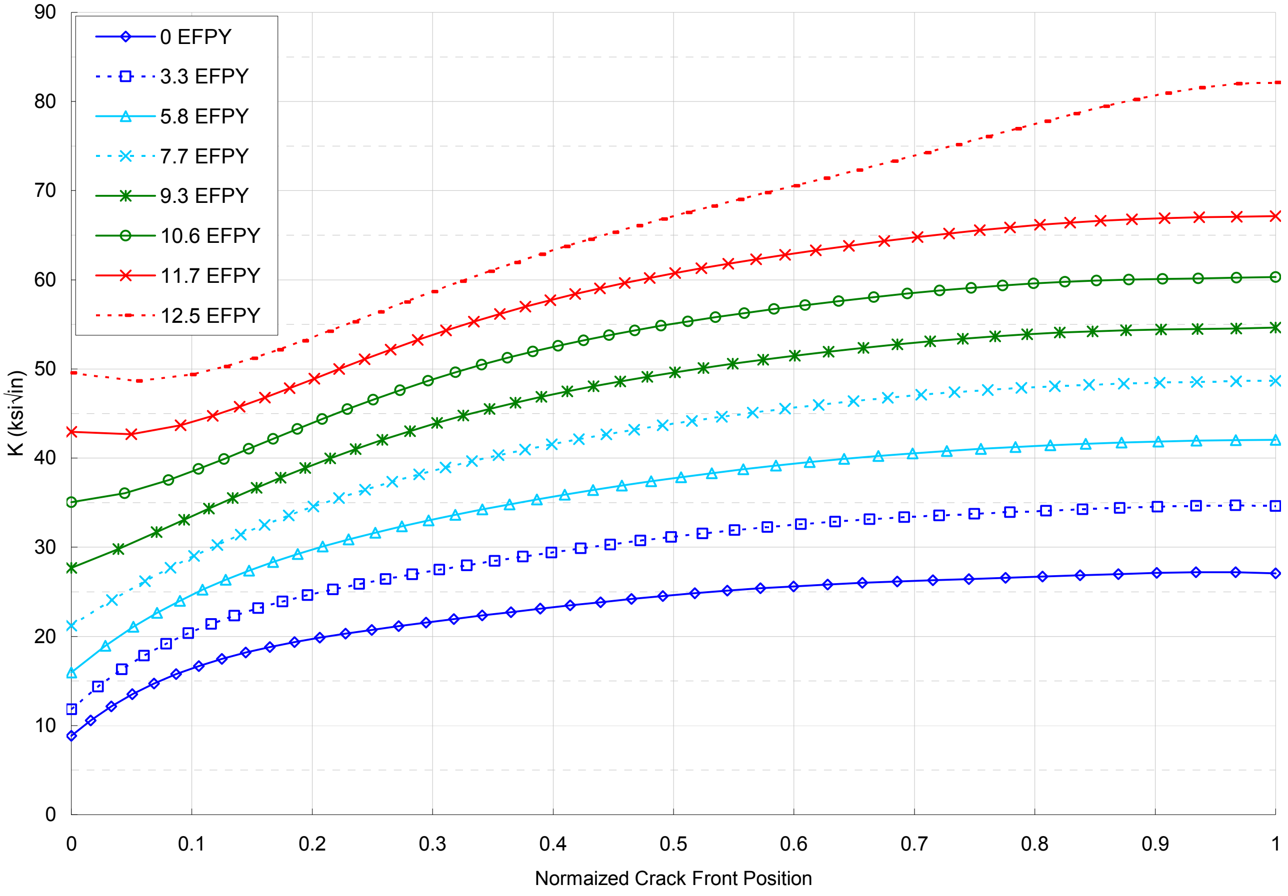

Figure 7-6: SIFs along Crack Front for ID Surface Flaws during PWSCC Growth with Initial Flaw of 14% Circumferential, 20% Depth, Case 1

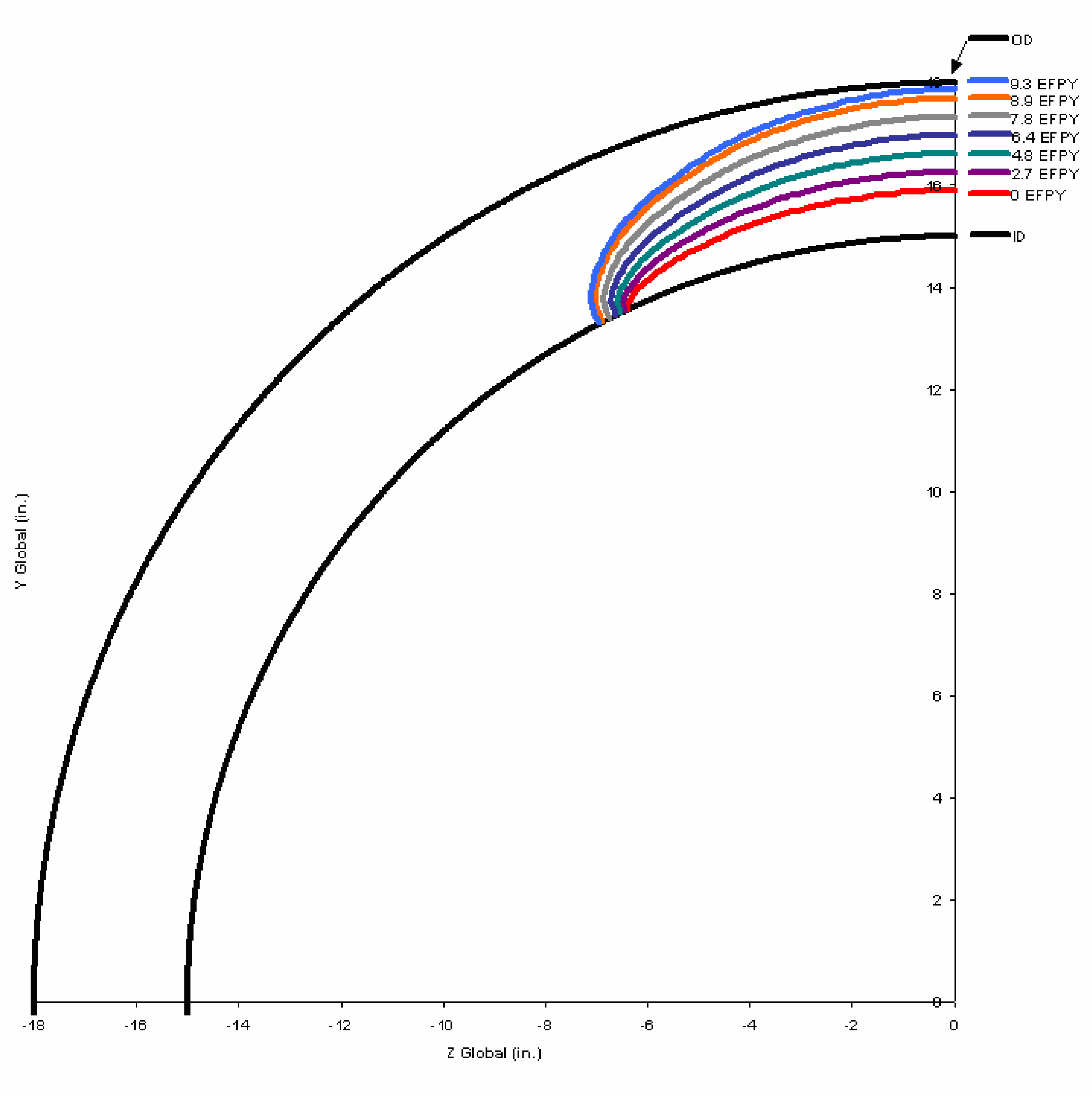

Figure 7-7: PWSCC Flaw Growth with Initial ID Surface Flaw of 14% Circumferential, 30% Depth, Case 2

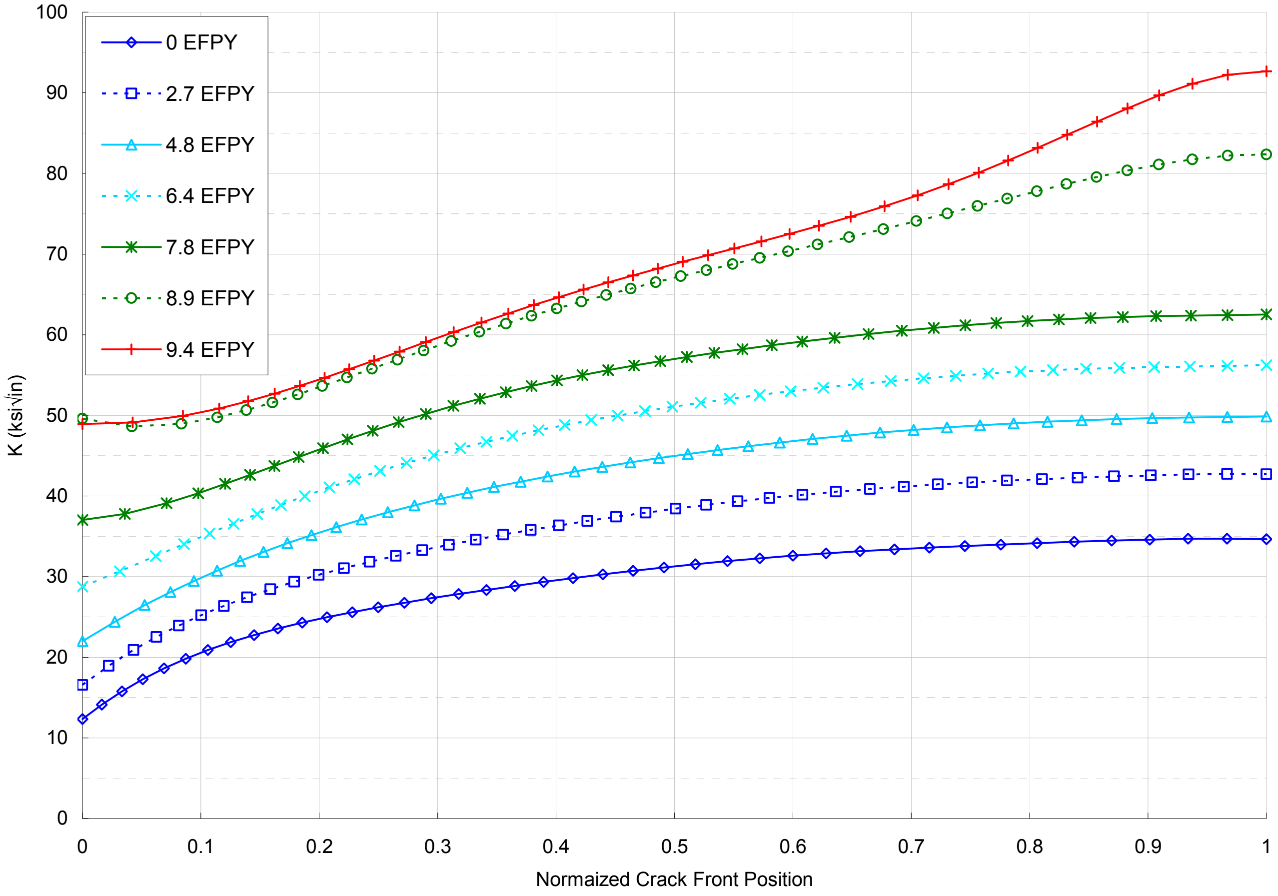

Figure 7-8: SIFs along Crack Front for ID Surface Flaws during PWSCC Growth with Initial Flaw of 14% Circumferential, 30% Depth, Case 2

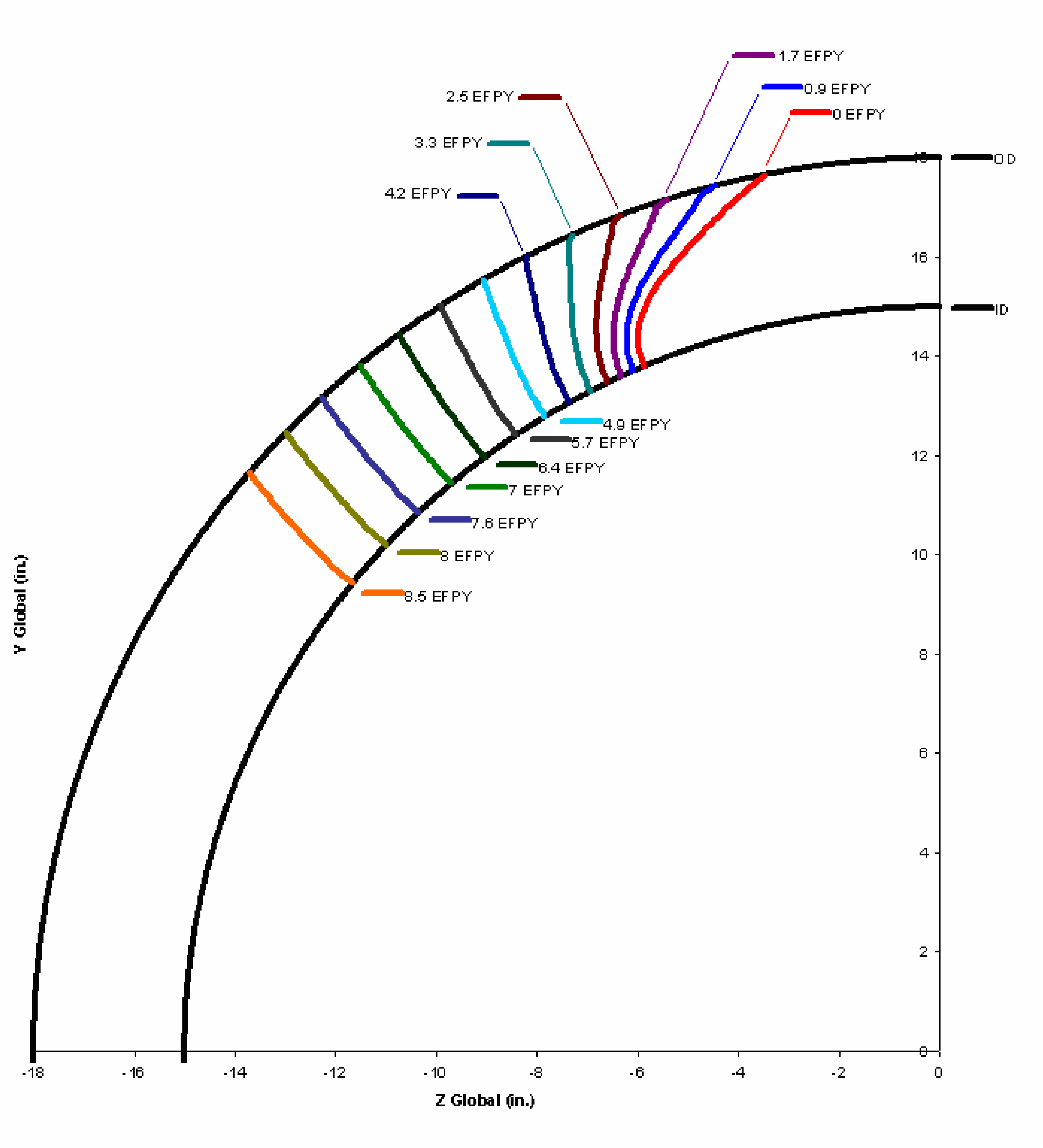

Figure 7-9: PWSCC Flaw Growth with Initial Through-wall Flaw of 14% Circumferential, Case 3

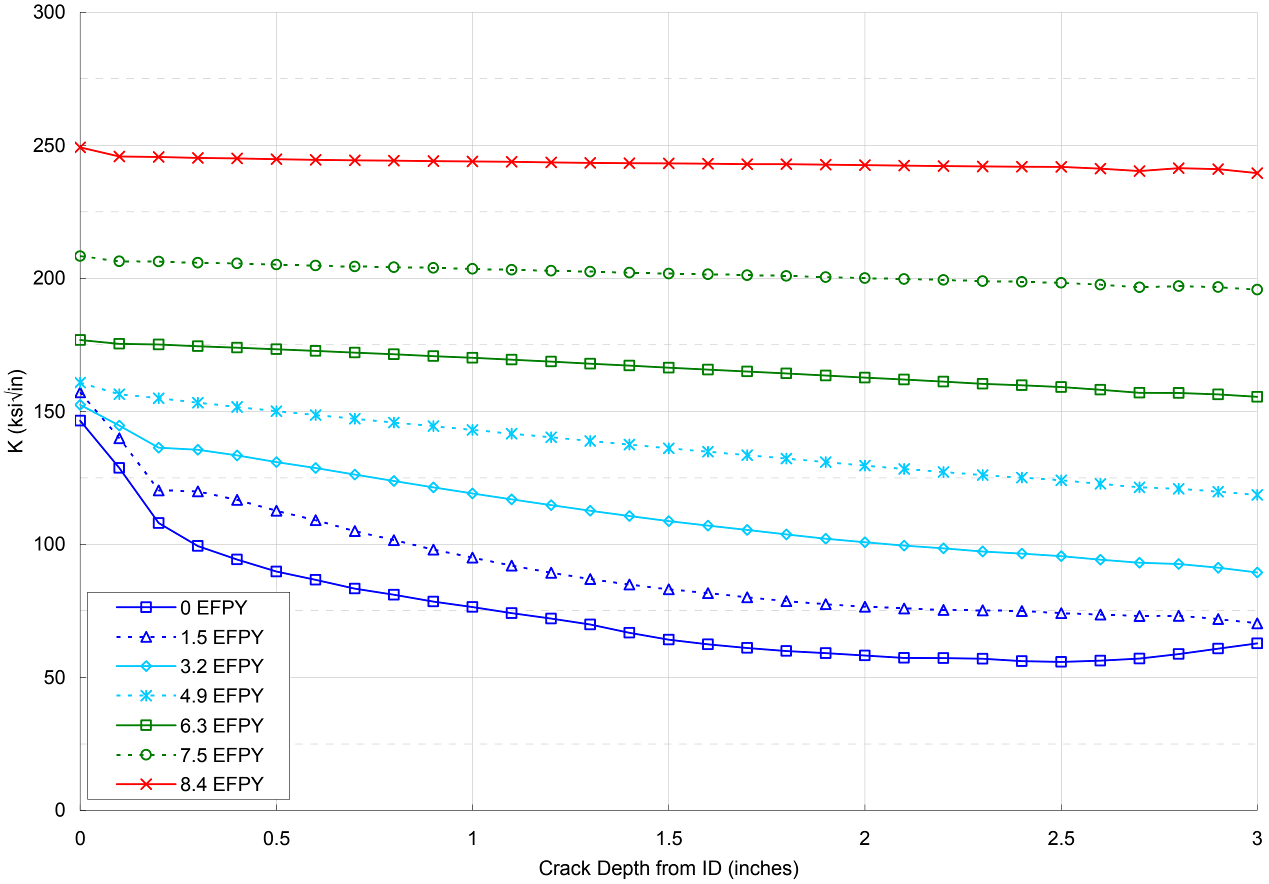

Figure 7-10: SIFs along Crack Front during PWSCC Flaw Growth with Initial Through-wall Flaw of 14% Circumferential, Case 3

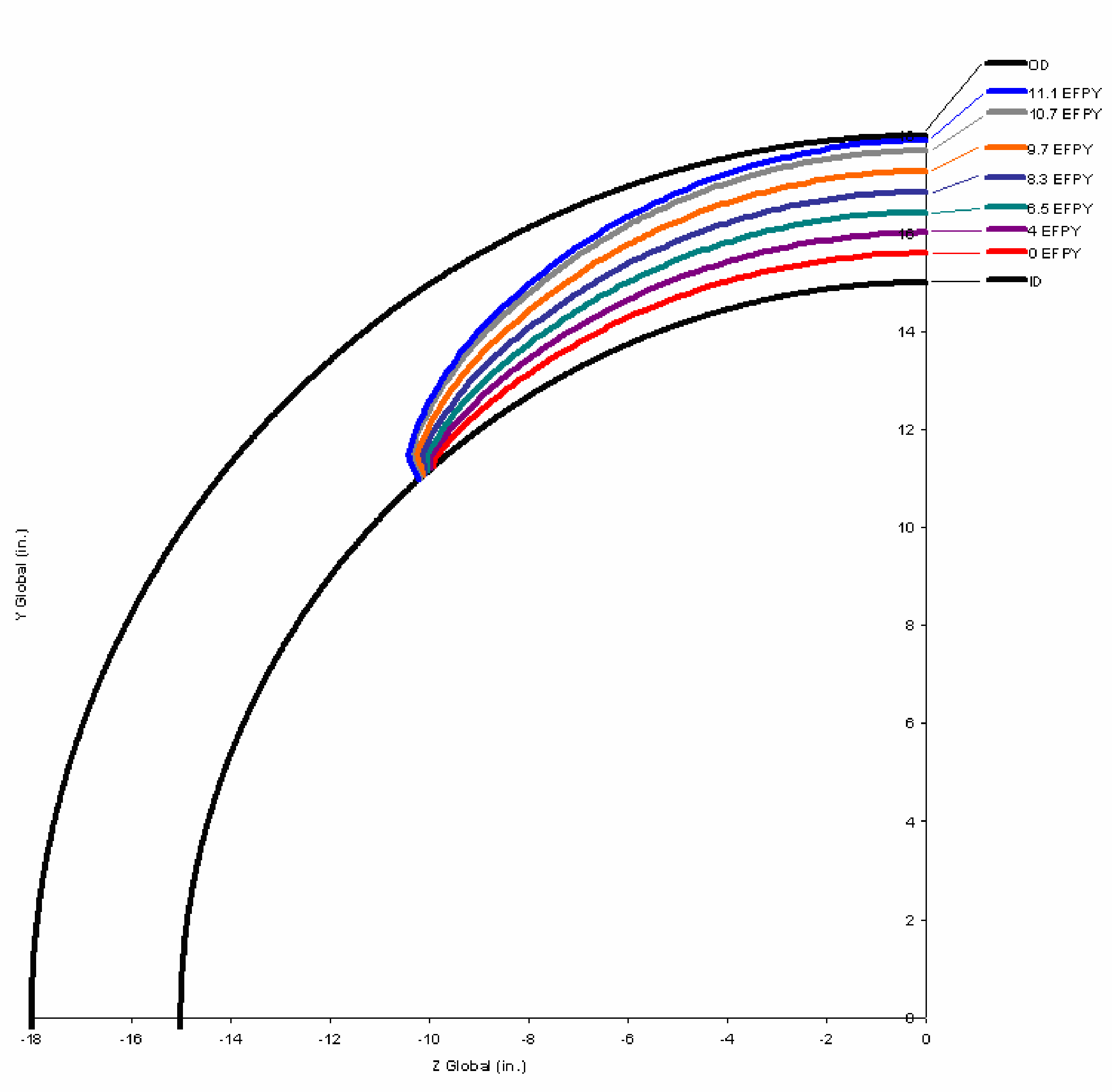

Figure 7-11: ID Surface PWSCC Flaw Growth with Initial Flaw Size of 23% Circumferential, 20% Depth, Case 4

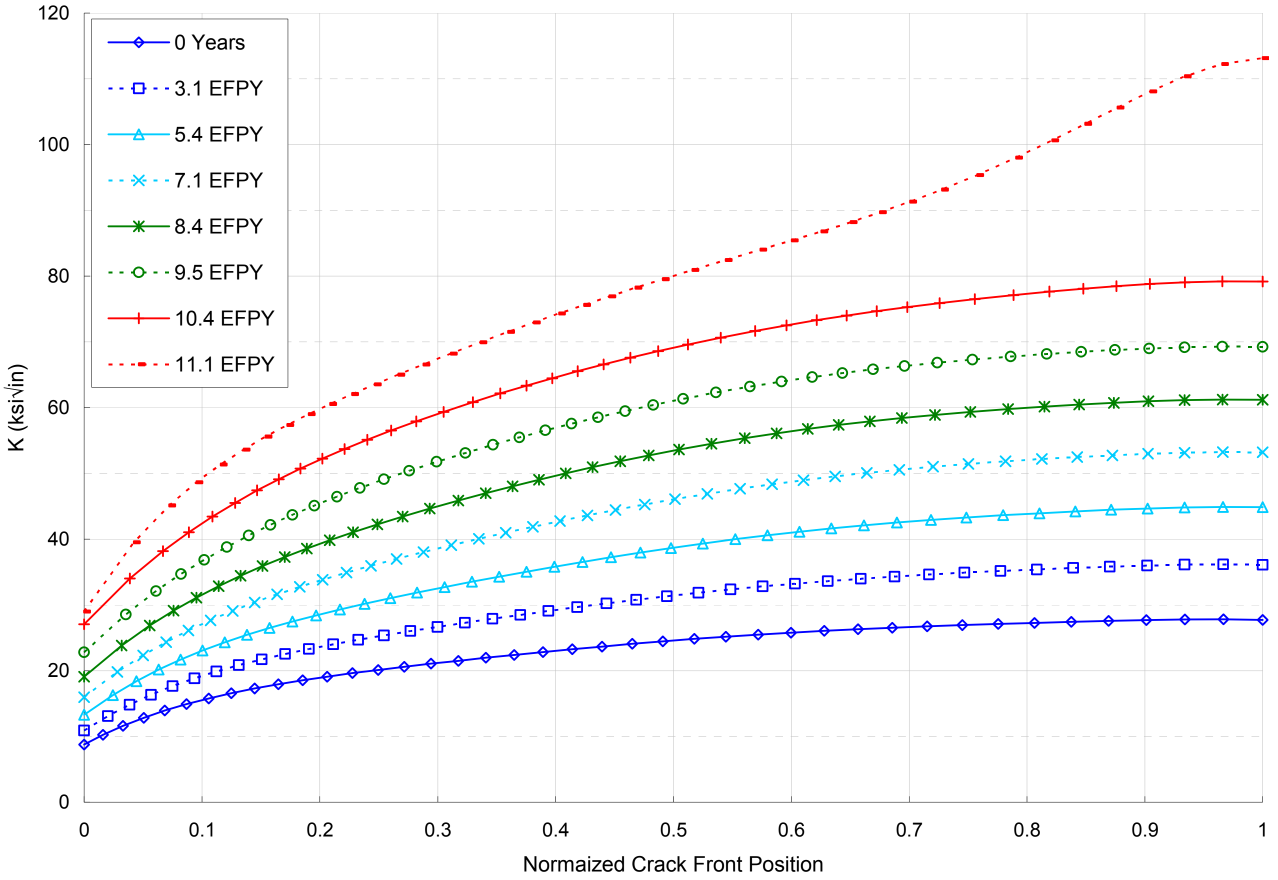

Figure 7-12: SIFs along Crack Front for ID Surface Flaws during PWSCC Growth with Initial Flaw of 23% Circumferential, 20% Depth, Case 4

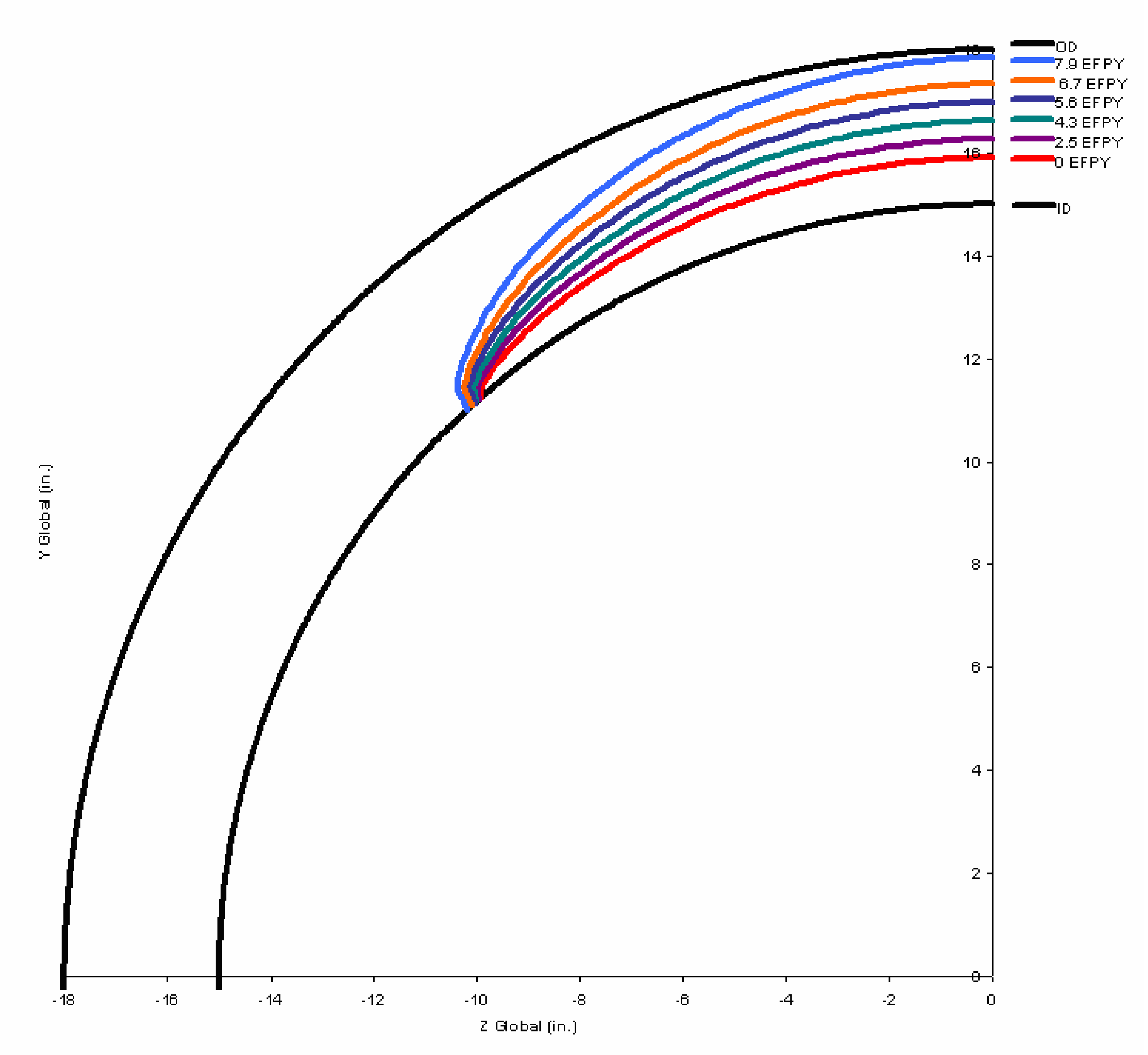

Figure 7-13: ID Surface PWSCC Flaw Growth with Initial Flaw of 23% Circumferential, 30% Depth, Case 5

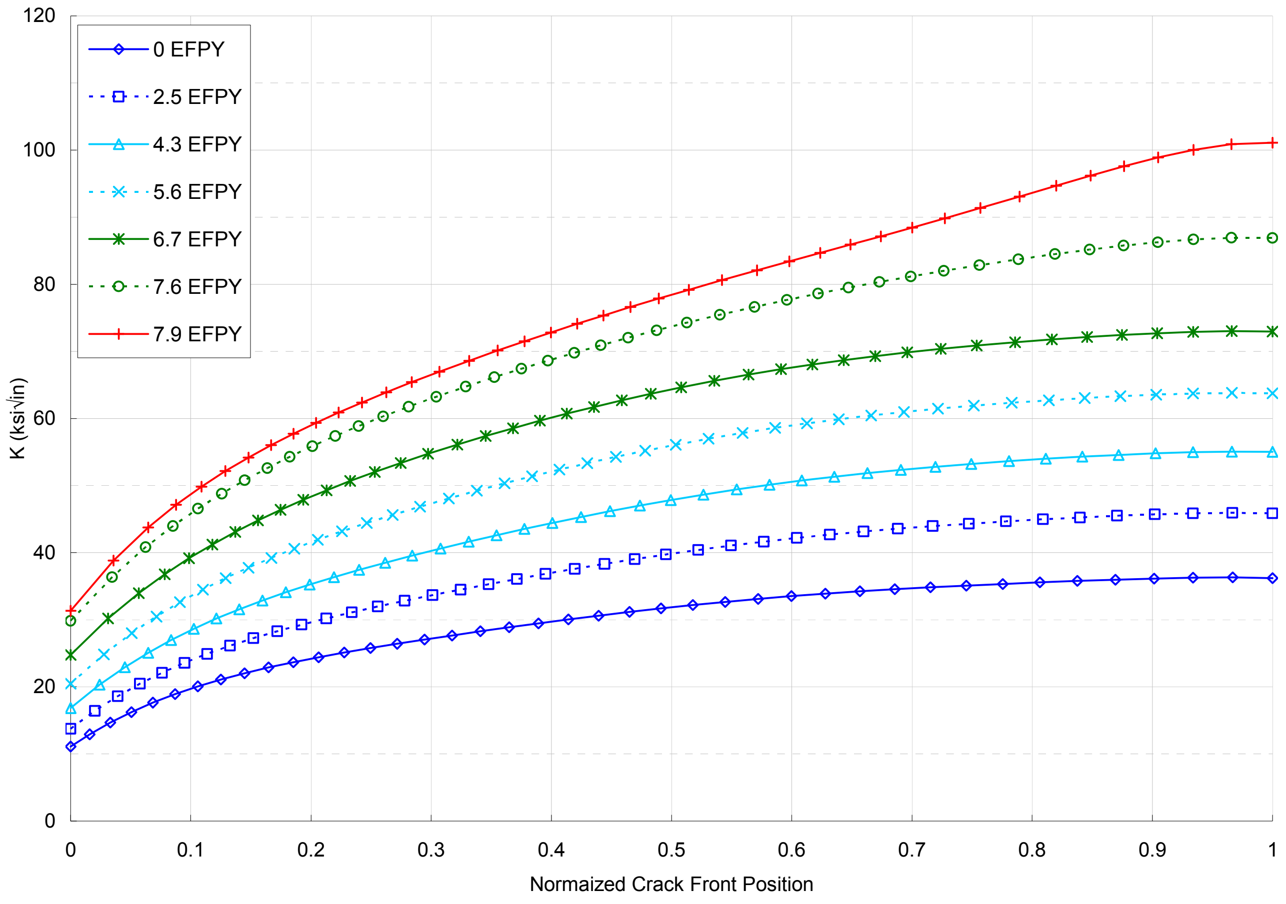

Figure 7-14: SIFs along Crack Front for ID Surface Flaws during PWSCC Growth with Initial Flaw of 23% Circumferential, 30% Depth, Case 5

8 PROBABILITY OF CRACKS

8.1 PURPOSE

The purpose of the probabilistic analysis was to assess the susceptibility of CE reactor coolant pump suction and discharge nozzles to PWSCC. The analysis considers available industry experience with the locations of Alloy 82/182 DM welds. More specifically, information included in the analysis included Alloy 82/182 DM welds that were nominally 28 inches in diameter or larger at the:

1. Reactor vessel inlet and outlet nozzles,
2. Steam generator inlet and outlet nozzles,
3. Reactor coolant pump suction and discharge nozzles, and
4. Pressurizer surge nozzle.

8.2 DESCRIPTION OF CALCULATION METHODOLOGY

The following process was used to calculate Weibull parameters and the corresponding probabilities of flaw indications.

Locations utilized in this analysis where large (greater than ~28” in diameter with ~3” wall thickness). These locations included plants with relevant Alloy 600 and Alloy 82/182 DM welds but varied by availability of data.

Locations where adjusted to effective full power years (EFPY), based on the plants capacity factor.

$$\boxed{EFPY = Age_{calendaryears} \times Capacity\ Factor}$$

To further reduce the variation between locations, the EFPYs were transformed to effective degradation years (EDY) using the following formula:

$$\boxed{EDY = EFPY \times \exp\left\{-\left(\frac{Q1}{R}\right)\left(\frac{1}{ActualTemp(F) + 459.7}\right) - \left(\frac{1}{\text{Reference Temp(F)} + 459.7}\right)\right\}}$$

where,

R = 1.103E-03 kcal/mole-R, and
$Q1$ = 50 kcal/mole.

To situate the locations as like-kind inputs, the final step is to adjust each flaw’s percent through-wall to the same depth, which was chosen as 7% of the wall thickness (7% tw). This depth was more or less arbitrary, but does correspond to the smallest depth of PWSCC flaw discovered in-service. To make this adjustment, an estimate of the time from 7% tw to the discovered depth in each component in the database was calculated. This time, in EFPY, was then Arrhenius temperature adjusted for the temperature of the component and subtracted from EDY at discovery. Resulting EDY value are seen as the best estimate as to when the flaw might have been at 7% tw.

Once the database was established and corrected for the fixed depth, the Weibull model was complete. It was then used to predict the probability of a flaw existing at the 7% tw depth. Three temperatures were selected for the analysis with the intent of covering the range of temperatures on the cold nozzle DM weld locations (548°F to 556°F), as well as a representative hot nozzle DM weld location (615°F). Results are presented in terms of the cumulative probability of a flaw with depth equal to 7% of the wall thickness, as a function of time, in EFPY, up to 60 EFPY.

The Weibull shape and scale parameters were generated using the Maximum Likelihood Estimation:

$$\boxed{\hat{\alpha} = \left[\frac{\sum_i x_i^{\beta}}{r}\right]^{\frac{1}{\beta}}} \qquad \text{Equation 8-1}$$

where,

α = scale,
β = shape,
r = number of failures, and
X = EDY of the i^{th} location.

Since both the shape and scale are unknown, a goal seek method is used to estimate the shape parameter. The method calculated the shape parameter when given a range of values for the scale parameter until they collectively best fit the input data. This method includes a reduced bias adjustment on the shape parameter.

Given the resulting Weibull shape and scale parameters, cumulative probabilities can be calculated using:

$$\boxed{1 - \exp\left\{-\left(\left(\frac{X}{\alpha}\right)^{\beta}\right)\right\}}$$

where,

X = EFPY

8.3 IMPORTANT ASSUMPTIONS

Serving the intent of the project, certain conservative assumptions have been made, such that portions of the analysis are not considered to be "best estimate" assumptions. The major assumption is the cracking data inputs from all the large DM weld locations are part of the same family with regard to cracking susceptibility. Therefore, all are relevant to be incorporated into the generation of Weibull shape and scale parameters. A reasonable counter argument can be made to this assumption, in that the different nozzle DM weld locations differ in one or more characteristics, including: the manufacturer, stress profile, surface finishing, and any applied mitigations, such as zinc addition. These differences were ignored, so all large nozzle DM weld indications could be utilized in the analysis. The judgment was made due to the additional confidence obtained by using this larger database outweighed the uncertainties resulting from the differences discussed above. These assumptions were verified by running separate cases, including multiple sets of data. The results showed independent of which inputs were included, the results for the cold leg temperature nozzles were not significantly changed.

A 7% through-wall flaw was assumed to be the smallest detectable flaw by performance demonstration initiative (PDI) qualified inspections. The accompanying figures show the probability of finding an indication at a 7% through-wall flaw. Multiple through-wall flaws of approximately 6% to 7% were found in the steam generator inlet nozzle DM welds in Japan.

8.4 RESULTS

The results summarized in Table 8-1, and shown graphically in Figure 8-1, Figure 8-2, and Figure 8-3, correspond to the different combinations of data discussed above. Figure 8-1 shows the probability of cracking for the pump nozzle DM welds, based on all the available inspection results, for reactor vessel nozzles, steam generator nozzles, pump nozzles, and pressurizer surge nozzles; this has been called Case 1. The next case, Case 2, includes all the nozzles except the pressurizer nozzles, and Case 3 includes only the reactor vessel and RCP nozzles.

The results show there is no discernable difference between the cases, with the probability of cracking for the pump nozzle DM welds being extremely low, even at 60 EFPY. Results indicate that even though DM welds have had many flaws at hot temperature locations, none have been found at cold temperature butt weld locations, and this gives a very low probability of flaws existing in cold temperature locations. Results in Table 8-1 show the highest probability of an indication was only 1.42%, at 60 EFPY (Case 1 at 556°F). A 60 EFPY value is well beyond a plant's licensed life, even with a 20-year life extension.

Table 8-1: Summary Results Table

At EFPY	Case 1	Case 2	Case 3
Temperature 548°F			
20	0.25%	0.00%	0.01%
40	0.57%	0.03%	0.05%
60	0.93%	0.12%	0.15%
Temperature 556°F			
20	0.38%	0.01%	0.02%
40	0.88%	0.10%	0.13%
60	1.42%	0.35%	0.35%
Temperature 615°F			
20	6.98%	20.92%	9.84%
40	15.32%	86.63%	44.34%
60	23.71%	99.92%	80.10%

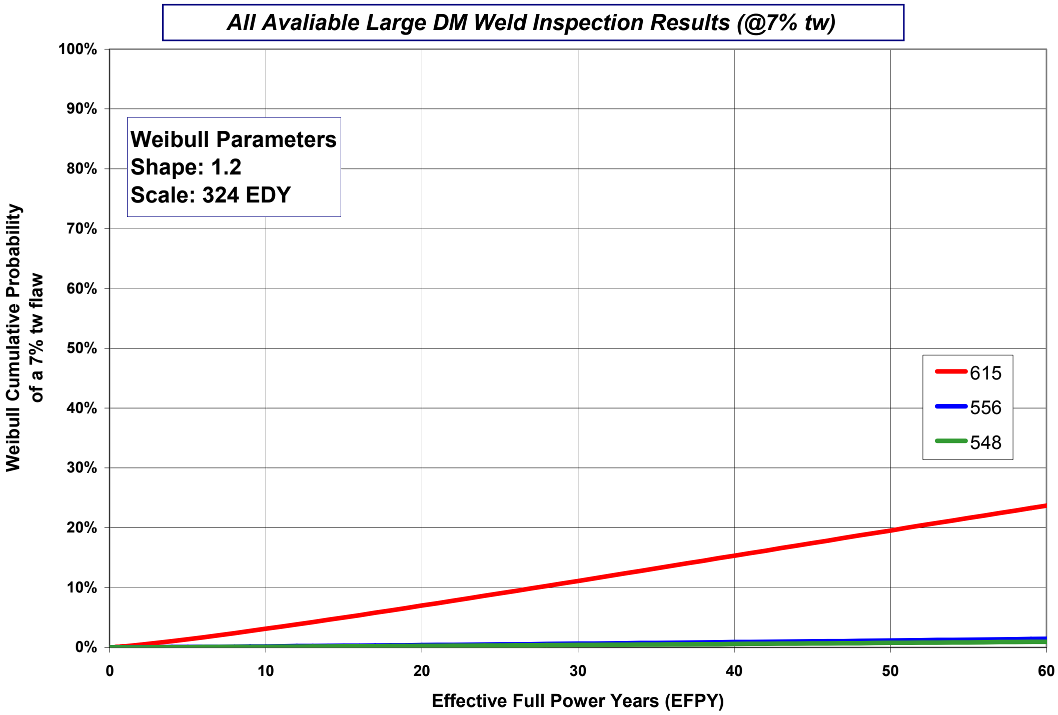

Figure 8-1: All Available Large DM Weld Inspection Results (7% Through-wall) – Case 1

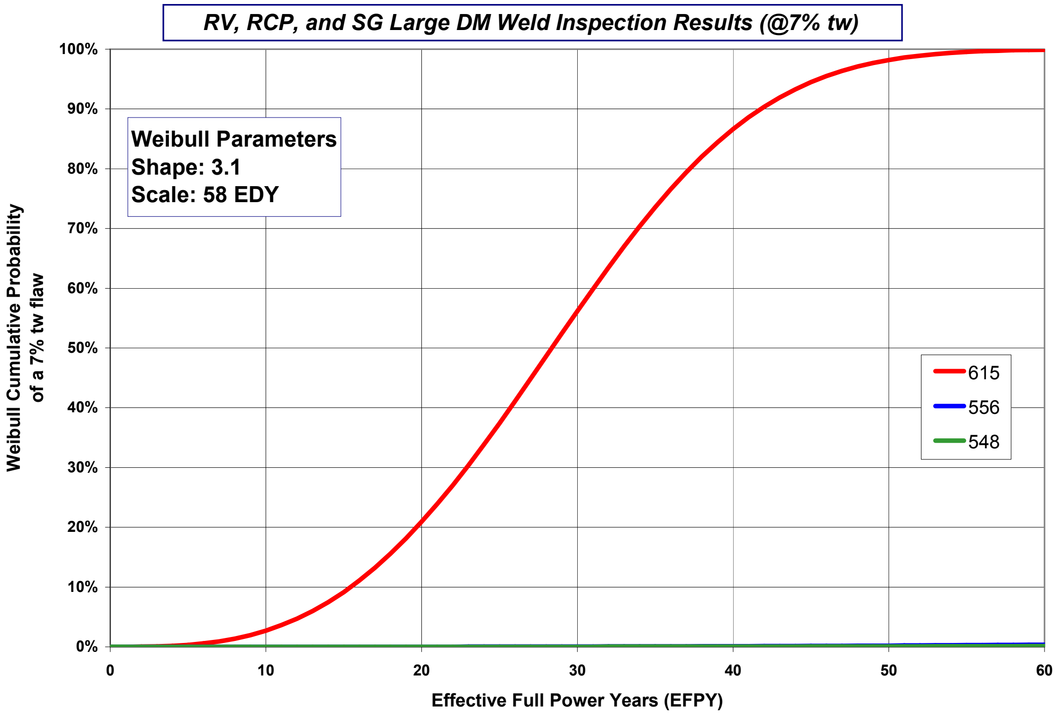

Figure 8-2: All Available Large DM Weld Inspection Results (7% Through-wall) – Case 2

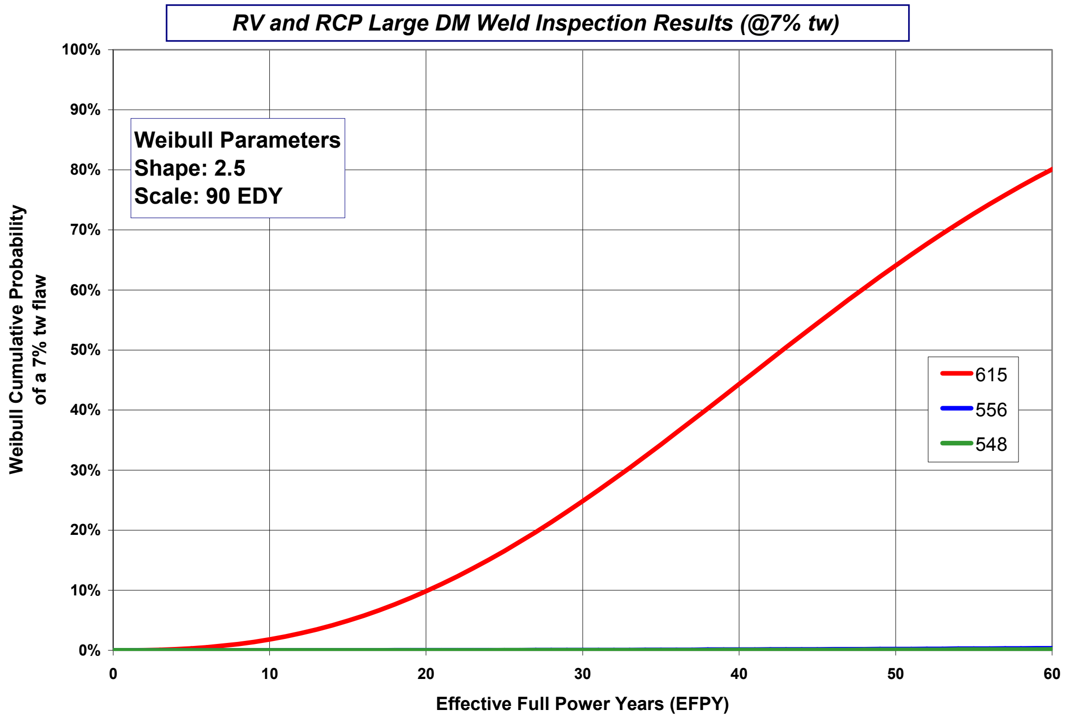

Figure 8-3: All Available Large DM Weld Inspection Results (7% Through-wall) – Case 3

9 PROPOSED CODE CHANGE

The inspection of Alloy 182/82 DM welds is presently being performed to the requirements of report MRP-139, Revision 1 [2]. These inspection requirements will be replaced by those of Code Case N-770 (see Appendix A), beginning in fall 2010, or shortly thereafter. MRP-139 [2] contains a provision which allows for a flaw tolerance calculation to justify the acceptability of inspection coverage less than the required 90%.

It is essential to revise Code Case N-770 to include a similar provision, and the work documented in this report forms the technical basis for such a revision. It is important to understand the locations for mitigation are practical and have, for the most part, already been mitigated, or are planned to be mitigated. A few regions, such as the pump nozzles of the CE fleet, do not lend themselves to mitigation, and a reasonable solution is to continue inspections at a frequency determined by the flaw tolerance of the region. In this case, the nozzles operate at cold leg temperatures and the probability of flaws is small. Any propagation from an existing flaw is also very slow, so the flaw tolerance is high. The results in this report suggest a ten year inspection frequency is justifiable for these regions.

The proposed change is shown below. There will be an additional sub-paragraph added under paragraph 2500 of the Code Case. The existing Code Case is reproduced as Appendix A of this report.

Proposed Revision to N-770 for Cold Leg Locations

Add Para -2500 (d):

For piping with diameters greater than or equal to 14 inches (355 mm), in locations with operating temperatures of less than 570ºF (299ºC), and where inspection coverage is limited by permanent obstructions, the following inspection coverage requirements of this case may be used in place of -2500(c):

(a) For axially oriented flaws, achieve the maximum coverage possible, and document any limitations, provided 90% coverage of the circumference is achieved.

(b) For circumferentially oriented flaws, achieve the maximum coverage possible, and document any limitations.

(c) If the coverage achieved in either (a) or (b) is less than 90%, perform the following flaw tolerance evaluations:

   a. Postulate a through-wall flaw in the region where inspection coverage is obstructed, with length equal to that which would yield the minimum detectable leakage for the plant. Calculate the critical through-wall length using IWB-3640, and show the time for the postulated flaw to reach a critical length is longer than the time to the next inspection, and

  b. Postulate a part-through semi-elliptic surface flaw in the region where inspection coverage is obstructed, with depth equal to 20% of the wall thickness, and length equal to the length of the largest obstruction. Calculate the Section XI allowable flaw depth using IWB- 3640, and show the time for the postulated flaw to reach the allowable size is longer than the time to the next inspection.

(d) If 90% coverage is not achieved for either axial or circumferential flaws, VT-2 examinations of the region are required during each refueling outage.

(e) If 90% coverage is not achieved for either axial or circumferential flaws, document the likelihood of leakage occurring at the location of interest between inspections, and document leakage monitoring action levels.

10 REFERENCES

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APPENDIX A: ASME CODE CASE N-770

Approval Date: January 26, 2009

The ASME Boiler and Pressure Vessel Standards Committee took action to eliminate Code Case expiration dates effective March 11, 2005. This means that all Code Cases listed in this Supplement and beyond will remain available for use until annulled by the ASME Boiler and Pressure Vessel Standards Committee.

Case N-770
Alternative Examination Requirements and Acceptance Standards for Class 1 PWR Piping and Vessel Nozzle Butt Welds Fabricated With UNS N06082 or UNS W86182 Weld Filler Material With or Without Application of Listed Mitigation Activities
Section XI, Division 1

Inquiry: What alternative examination requirements and acceptance standards to those of Section XI, Table IWB-2500-1, Examination Category B-F and Examination Category B-J; or Nonmandatory Appendix R, Table R-2500-1, Examination Category R-A, Item No. R1.15; and IWA-4530, IWB-2200, IWB-2400, and IWB-3000, may be used for Class 1 PWR piping and vessel nozzle butt welds fabricated with Alloy 82/182[1] material with or without the application of mitigation activities?

Reply: It is the opinion of the Committee that the following alternatives to the examination requirements and acceptance standards of Section XI, Table IWB-2500-1, Examination Category B-F, and Examination Category B-J; or Nonmandatory Appendix R, Table R-2500-1, Examination Category R-A, Item No. R1.15; and IWA-4530, IWB-2200, IWB-2400, and IWB-3000, may be used for Class 1 PWR piping and vessel nozzle butt welds fabricated with weld filler material UNS N06082 (SFA-5.14, ERNiCr-3) or UNS W86182 (SFA-5.11, ENiCrFe-3), or a combination of both, with or without the types of mitigation listed in -2410(a). These individual filler materials or a combination of both will be hereinafter referred to as Alloy 82/182[1] material.

-1000 SCOPE AND RESPONSIBILITY

-1100 SCOPE

(a) Except as stated in -1100(c) through -1100(f), this Case provides alternative examination requirements and acceptance standards for volumetric examination of NPS 2 (DN 50) and greater and visual examination of greater than NPS 1 (DN 25) pressure retaining Class 1 PWR piping and vessel nozzle butt welds fabricated with Alloy 82/182 materials, with or without application of mitigation activities. Pressurizer nozzle butt welds are considered part of the hot leg welds.

(b) This Case may not be used to perform mitigation activities. For the types of mitigation activities identified in -2410(a), this Case provides pre-mitigation examination requirements, configuration requirements, stress improvement performance criteria, and preservice examination requirements.

(c) Butt welds described in (a) above with normal operating temperatures of less than 525°F (274°C) are not included in this Case.

(d) Pressure retaining welds in control rod drive and instrument nozzle housings of reactor vessel heads are not included in this Case.

(e) Alloy 82/182 welds never exposed to the reactor water environment are not included in this Case.

(f) If a mitigated or unmitigated butt weld initially included in -1100(a) is subsequently completely removed and replaced with PWSCC resistant materials, the weld will no longer be included in the scope of this Case. The weld shall be added to the ISI Program as a new weld in accordance with IWB-2412(b) in editions and addenda up to and including the 2006 Addenda and in accordance with IWB-2411(b) in the 2007 Edition or later editions and addenda.

-1200 COMPONENTS SUBJECT TO EXAMINATION

-1210 EXAMINATION REQUIREMENTS

The examination requirements shall apply to the following:

(a) Class 1 piping and vessel nozzle butt welds fabricated with Alloy 82/182 material with non-welded stress improvement mitigation or without mitigation.

(b) Class 1 piping and vessel nozzle butt welds fabricated with Alloy 82/182 material and mitigated with weld

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[1] Alloy 82 and Alloy 182 are common abbreviations used by industry, the regulatory authority, and research organizations for UNS N06082 (SFA-5.14, ERNiCr-3) and UNS W86182 (SFA-5.11, ENiCrFe-3), respectively.

overlay, inlay or cladding with either, or any combination of weld filler materials UNS N06052 (SFA-5.14, ERNiCrFe-7), UNS W86152 (SFA 5.11, ENiCrFe-7), or UNS N06054 (SFA-5.14, ERNiCrFe-7A). These individual filler materials or any combination thereof will be hereafter referred to as Alloy 52/152.[2]

-2000 EXAMINATION

-2200 BASELINE EXAMINATION

The examinations listed in Table 1 applicable to the configurations of welds within the scope of -1100 shall be performed in accordance with -2500 completely, once, as a baseline examination and shall be evaluated by comparing the examination results with the acceptance standards in -3132. Inspection Items A-1, A-2, and B of Table 1 describe butt welds which have not been mitigated while Inspection Items C through K describe butt welds which have been mitigated using one of the following techniques: full structural weld overlay, stress improvement, inlay, or cladding. For Inspection Items C through K, the preservice examination (-2220) establishes the baseline examination. These examinations shall include all piping and vessel nozzle butt welds within the scope of -1100. Examinations performed prior to implementation of this Case that meet the requirements of Table 1 and Section XI, Appendix VIII may be credited. Welds in Table 1 Inspection Item A-1, A-2, and B that have not been examined using Section XI, Appendix VIII requirements shall be examined within the next two refueling outages from adoption of this Case. Welds in all other categories shall be scheduled in accordance with Table 1.

-2220 PRESERVICE EXAMINATION AFTER REPAIR/REPLACEMENT ACTIVITIES OR STRESS IMPROVEMENT

Prior to return to service, the applicable examinations listed in Table 1 shall be performed on items affected by a repair/replacement activity (mitigation by weld overlay, stress improvement with welding, inlay, or cladding), or by mitigation using non-welded stress improvement methods. Preservice examinations shall meet the acceptance standards of Table 1. Preservice acceptance in accordance with -3132.3 is not permitted for flaws in new weld material applied with the mitigation techniques defined in Table 1. Previously evaluated flaws in the dissimilar metal weld that were mitigated by the techniques identified in Table 1 need not be reevaluated unless the previously evaluated flaws have grown or new planar flaws have been identified.

-2400 EXAMINATION SCHEDULE

-2410 EXAMINATION PROGRAM

(a) Inservice examination methods and frequencies as required by Table 1 shall be determined using the following parameters to characterize the susceptibility to crack initiation, the potential for crack propagation, and the mitigation technique.

(1) Susceptibility to crack initiation is categorized by the operating temperature of the component, as follows:

(a) Hot leg temperatures [defined as temperatures ≥ 580°F (304°C)]

(1) The hot leg is further divided into items at operating temperatures > 625°F (329°C) (item A-1) and items at operating temperature ≤ 625°F (329°C) (item A-2)

(b) Cold leg temperatures [defined as temperatures ≥ 525°F (274°C) and < 580°F (304°C)]

(2) The potential for crack propagation is categorized by the status of the weld as follows:

(a) cracked

(b) uncracked

(3) The following mitigation techniques are included in this Case:

(a) Full Structural Weld Overlay;

(b) Stress Improvement — with or without welding: Stress Improvement techniques shall meet the Performance Criteria and Measurement or Quantification Criteria of Appendix I;

(c) Inlay; and

(d) Cladding

(b) Welds included in -1100 shall be identified as a unique population within the ISI Program and examined in accordance with the requirements of Table 1.

(c) The mitigated welds in Table 1, Inspection Items C through K, shall be added to the ISI Program as new welds in accordance with IWB-2412(b) in editions and addenda up to and including the 2006 Addenda and in accordance with IWB-2411(b) in the 2007 Edition and later editions or addenda.

-2420 SUCCESSIVE EXAMINATIONS

Successive examinations are specified in Table 1.

-2430 ADDITIONAL EXAMINATIONS

(a) Examinations performed in accordance with Table 1 that reveal unacceptable flaws as defined in -2430(a) (1),

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[2] Alloy 52, Alloy 152, and other similar designations are common abbreviations used by industry, the regulatory authority, and research organizations for UNS N06052 (SFA 5.14, ERNiCrFe-7), UNS W86152 (SFA-5.11, ENiCrFe-7), and UNS N06054 (SFA 5.14, ERNiCrFe-7A), respectively. For the purposes of this Case, these materials are considered equivalent.

TABLE 1
EXAMINATION CATEGORIES

CLASS 1 PWR PRESSURE RETAINING DISSIMILAR METAL PIPING AND VESSEL NOZZLE BUTT WELDS CONTAINING ALLOY 82/182

Inspection Item	Parts Examined	Examination Requirements/ Fig. No.	Examination Method (1)	Acceptance Standard	Extent and Frequency of Examination	Deferral of Examination to End of Interval
A-1	Unmitigated butt weld at Hot Leg operating temperature (-2410) > 625°F (329°C)	Weld Surface Fig. 1	Visual (2), (3) Volumetric (4)	-3140 -3130	Each refueling outage Every second refueling outage (5)	Not permissible
A-2	Unmitigated butt weld at Hot Leg operating temperature (-2410) ≤ 625°F (329°C)	Weld Surface Fig. 1	Visual (2), (3) Volumetric (4)	-3140 -3130	Each refueling outage Every 5 years (5)	Not permissible
B	Unmitigated butt weld at Cold Leg operating temperature (-2410) ≥ 525°F (274°C) and < 580°F (304°C)	Weld Surface Fig. 1	Visual (2), (3) Volumetric (4)	-3140 -3130	Once per interval Every second inspection period not to exceed 7 years (5)	Not permissible
C	Uncracked (6) butt weld reinforced by full structural weld overlay of Alloy 52/152 (7) material	Fig. 2	Volumetric (4), (8), (9)	-3130	These welds shall be placed into a population to be examined on a sample basis. Twenty-five percent of this population shall be added to the ISI Program in accordance with -2410 and shall be examined once each inspection interval (10).	[Note (11)]
D	Uncracked butt weld mitigated with stress improvement (12), (20)	Fig. 1 or 5	Volumetric (4), (13), (14)	-3130	Examine within 10 years following stress improvement application. If multiple welds are mitigated in the same inspection period, examinations shall be spread throughout years 3 through 10 following application, similar to provisions in -2410(c). Examination volumes that show no indication of cracking shall be placed into a population to be examined on a sample basis. Twenty-five percent of this population shall be added to the ISI Program in accordance with -2410 and shall be examined once each inspection interval (10). If more than one type of stress improvement is used, the population of each type of stress improved welds shall be established and 25% of each type shall be added to the ISI Program in accordance with -2410 and shall be examined once each inspection interval (10).	[Note (11)]

TABLE 1
EXAMINATION CATEGORIES (CONT'D)

CLASS 1 PWR PRESSURE RETAINING DISSIMILAR METAL PIPING AND VESSEL NOZZLE BUTT WELDS CONTAINING ALLOY 82/182

Inspection Item	Parts Examined	Examination Requirements/ Fig. No.	Examination Method (1)	Acceptance Standard	Extent and Frequency of Examination	Deferral of Examination to End of Interval
E	Cracked butt weld mitigated with stress improvement (12), (20)	Fig. 1 or 5	Volumetric (4), (13), (14)	-3130	Once during the first or second refueling outage following application of stress improvement. Examination volumes that show no indication of crack growth or new cracking shall be placed into a population to be examined on a sample basis. Twenty-five percent of this population shall be added to the ISI Program in accordance with -2410 and shall be examined once each inspection interval (10). If more than one type of stress improvement is used, the population of each type of stress improved welds shall be established and 25% of each type shall be added to the ISI Program in accordance with -2410 and shall be examined once each inspection interval (10).	[Note (11)]
F	Cracked butt weld reinforced by full structural weld overlay of Alloy 52/152 material	Fig. 2	Volumetric (4), (8), (9)	-3130	Once during the first or second refueling outage following overlay. Weld overlay examination volumes that show no indication of crack growth or new cracking shall be placed into a population to be examined on a sample basis. Twenty-five percent of this population shall be added to the ISI Program in accordance with -2410 and shall be examined once each inspection interval (10).	[Note (11)]
G	Uncracked butt weld mitigated with Alloy 52/152 inlay material (15)	Fig. 3	Volumetric (4), (16) Surface (17)	-3130	Perform a volumetric examination (16) and a surface examination (17) of all welds no sooner than the third refueling outage and no later than the shorter of 10 years following inlay or the design life of the inlay. Examination volumes that show no indications of cracking shall be placed into a population to be examined on a sample basis. Twenty-five percent of this population shall receive a volumetric examination (18) performed from the outside diameter surface, or a volumetric examination (16) and a surface examination (17) performed from the weld inside diameter surface. The 25% sample shall be added to the ISI Program in accordance with -2410 and shall be examined once each inspection interval (10).	[Note (11)]

TABLE 1
EXAMINATION CATEGORIES (CONT'D)

CLASS 1 PWR PRESSURE RETAINING DISSIMILAR METAL PIPING AND VESSEL NOZZLE BUTT WELDS CONTAINING ALLOY 82/182

Inspection Item	Parts Examined	Examination Requirements/ Fig. No.	Examination Method (1)	Acceptance Standard	Extent and Frequency of Examination	Deferral of Examination to End of Interval
H	Uncracked butt weld mitigated with corrosion resistant cladding (15)	Fig. 4	Volumetric (4), (16) Surface (17)	-3130	Perform a volumetric examination (16) and a surface examination (17) of all welds no sooner than the third refueling outage and no later than the shorter of 10 years following cladding or the design life of the cladding. Examination volumes that show no indications of cracking shall be placed into a population to be examined on a sample basis. Twenty-five percent of this population shall receive a volumetric examination (18) performed from the outside diameter surface, or a volumetric examination (16) and a surface examination (17) performed from the weld inside diameter surface. The 25% sample shall be added to the ISI Program in accordance with -2410 and shall be examined once each inspection interval (10).	[Note (11)]
J	Cracked butt weld mitigated with Alloy 52/152 inlay material (15)	Fig. 3	Volumetric (4), (16) Surface (17)	-3130	Once during the first or second refueling outage following application of inlay. This examination shall include a volumetric examination (16) and a surface examination (17). Examination volumes that show no indications of new cracking or crack growth shall be placed into a population to be examined on a sample basis. Twenty-five percent of this population shall receive a volumetric examination (18) performed from the outside diameter surface, or a volumetric examination (16) and a surface examination (17) performed from the weld inside diameter surface. The 25% sample shall be added to the ISI Program in accordance with -2410 and shall be examined once each inspection interval (10).	[Note (11)]

TABLE 1
EXAMINATION CATEGORIES (CONT'D)

CLASS 1 PWR PRESSURE RETAINING DISSIMILAR METAL PIPING AND VESSEL NOZZLE BUTT WELDS CONTAINING ALLOY 82/182

Inspection Item	Parts Examined	Examination Requirements/ Fig. No.	Examination Method (1)	Acceptance Standard	Extent and Frequency of Examination	Deferral of Examination to End of Interval
K	Cracked butt weld mitigated with corrosion resistant cladding (15)	Fig. 4	Volumetric (4), (16) Surface (17)	-3130	Once during the first or second refueling outage following application of cladding. This examination shall include a volumetric examination (16) and a surface examination (17). Examination volumes that show no indications of new cracking or crack growth shall be placed into a population to be examined on a sample basis. Twenty-five percent of this population shall receive a volumetric examination (18) performed from the outside diameter surface, or a volumetric examination (16) and a surface examination (17) performed from the weld inside diameter surface. The 25% sample shall be added to the ISI Program in accordance with -2410 and shall be examined once each inspection interval (10).	[Note (11)]

GENERAL NOTE: Alloy 82 and Alloy 182 are common abbreviations used by industry, the regulatory authority, and research organizations for UNS N06082 (SFA-5.14, ERNiCr-3) and UNS W86182 (SFA-5.11, ENiCrFe-3), respectively. These individual filler materials or a combination of both are referred to as Alloy 82/182.

NOTES:

(1) Volumetric examination requirements, methods, acceptance standards and frequencies are applicable to Class 1 PWR piping and vessel nozzle butt welds NPS 2 (DN 50) or greater.

(2) A VE shall consist of the following:
  (a) A direct examination of the bare metal surface of the entire outer surface of the weld with the insulation removed or lifted to allow access for the VE.
  (b) The direct VE shall be performed at a distance not greater than 4 ft (1.2 m) from the weld and with a demonstrated illumination level sufficient to allow resolution of lower case characters having a height of not greater than 0.105 in. (2.7 mm).
  (c) Alternatively, the VE may be performed with insulation in place or removed using remote visual equipment that provides resolution of the weld metal surface equivalent to a bare metal direct VE as defined in (a) and (b), above.
  (d) Personnel performing the VE shall be qualified as a VT-2 visual examiner and shall have completed at least four (4) hours of additional training in detection of borated water leakage from Alloy 600/82/182 components and the resulting boric acid corrosion of adjacent ferritic steel components.
  (e) Examination may be performed with the system depressurized.

(3) A VE may be performed during an outage when a volumetric examination is performed from the weld outer surface. An ultrasonic examination performed from the component inside or outside surface in accordance with the requirements of Table 1 and Appendix VIII (1995 Edition with the 1996 Addenda or later) shall be acceptable in lieu of the VE requirement of this table.

(4) Ultrasonic volumetric examination shall be used and shall meet the applicable requirements of Appendix VIII.

(5) Subsequent Inservice Inspection of Unmitigated Welds With Inside Surface Connected Planar Flaws
  (a) If planar surface flaws are detected in the butt weld/base metal inside surface, this weld shall be reexamined at the shorter frequency of every refueling outage or the frequency determined by the crack growth analysis of -3132.3.
  (b) This weld shall be subsequently examined at the frequency required by (a) unless mitigated.

TABLE 1
EXAMINATION CATEGORIES (CONT'D)

NOTES (CONT'D):

(6) Pre-weld Overlay Examination for Full Structural Weld Overlay
  - (a) Except as provided in (b) below, if volumetric examination was not performed on the weld prior to structural weld overlay, the weld shall be assumed cracked and shall be classified Inspection Item F. This examination prior to weld overlay shall include the examination volume in Fig. 1.
  - (b) For reactor vessel nozzle welds at cold leg temperatures requiring the core internals to be removed to perform the examination, the volumetric examinations are not required prior to application of the weld overlay. If the pre-weld overlay volumetric examination is not performed, a post-weld overlay preservice examination consisting of a surface examination [Note (19)] and a volumetric examination shall be performed after removal of the core internals. If these examinations do not detect cracks, the weld shall be considered uncracked and shall be subject to the examination requirements of Inspection Item C. This post-weld overlay volumetric examination shall include the examination volume in Fig. 1 and the examination volume in Fig. 2(a).
  - (c) If the crack is completely removed by a repair/replacement activity in accordance with IWA-4000 and the weld overlay is then applied, the weld shall be reclassified as Inspection Item C.

(7) Alloy 52, Alloy 152, and other similar designations are common abbreviations used by industry, the regulatory authority, and research organizations for UNS N06052 (SFA-5.14, ERNiCrFe-7), UNS W86152 (SFA-5.11, ENiCrFe-7), and UNS N06054 (SFA- 5.14, ERNiCrFe-7A), respectively. These individual filler materials or any combination thereof are referred to as Alloy 52/152.

(8) Inservice Inspection of Full Structural Weld Overlay
  - (a) The weld overlay examination volume in Fig. 2(a) shall be ultrasonically examined to determine the acceptability of the weld overlay and to determine if any new or existing cracks have propagated into the outer 25% of the original weld or base material or into the overlay. The angle beam shall be directed perpendicular and parallel to the piping axis, with scanning performed in four directions.
  - (b) The weld overlay shall meet the inservice examination standards of IWB-3514. In applying the acceptance standards to planar indications, the thickness t_1 or t_2, defined in Fig. 2(b), shall be used as the nominal wall thickness in IWB-3514, provided the base material beneath the flaw (i.e., safe end, nozzle, or piping material) is not susceptible to PWSCC. For susceptible material, t_1 shall be used. If the acceptance standards of IWB-3514 cannot be met, the weld overlay shall meet the acceptance standards of IWB-3600. Any indication characterized as stress corrosion cracking in the weld overlay material is unacceptable.
  - (c) As an alternative to (a), for inservice inspection, the weld examination volume in Fig. 1 may be ultrasonically examined. If cracking is detected extending beyond the weld examination volume, the weld examination of (a) and (b) above shall be performed to determine the acceptability of the weld overlay.
  - (d) If inservice examinations of (a), (b), or (c) reveal crack growth, or new cracking in the weld overlay or outer 25% of original weld/base material meeting the acceptance standards, the weld overlay examination volume shall be reexamined during the first or second refueling outage following discovery of the crack growth or new cracking. The weld overlay examination volume shall be subsequently examined two additional times at the period of one or two refueling outages, i.e., a total of 3 examinations within 6 refueling outages.
  - (e) If the examinations required by (d) reveal that the flaws remain essentially unchanged for three successive examinations, the weld examination schedule may revert to the sample and schedule of examinations identified in Table 1.

(9) Preservice Inspection for a Full Structural Weld Overlay
  - (a) The examination volume in Fig. 2(a) shall be ultrasonically examined. The angle beam shall be directed perpendicular and parallel to the piping axis, with scanning performed in four directions, to locate and size any planar flaws that have propagated into the outer 25% of the original weld or base metal thickness or into the weld overlay. For weld overlays on cast austenitic stainless steel base materials, if a 100% through-wall flaw is used for the crack growth analysis, only planar flaws that have propagated into the weld overlay or are in the overlay are required to be located and sized.
  - (b) The preservice examination acceptance standards of IWB-3514 shall be met for flaws in the weld overlay material. In applying the acceptance standards to planar indications, the thickness, t_1 or t_2, defined in Fig. 2(b), shall be used as the nominal wall thickness in IWB-3514, provided the base material beneath the flaw (i.e., safe end, nozzle, or piping material) is not susceptible to PWSCC. For susceptible material, t_1 shall be used. Planar flaws in the outer 25% of the original weld or base material thickness shall meet the design analysis requirements of -3132.3(d).
  - (c) The flaw evaluation requirements of IWB-3640 shall not be applied to planar flaws in the weld overlay material, identified during preservice examination, that exceed the preservice examination acceptance standards of IWB-3514.

(10) The 25% sample shall consist of the same welds in the same sequence during successive intervals to the extent practical provided the 25% sample contains the welds that experience the highest operating temperature in the Inspection Item. If hot leg and cold leg welds are included in the same Inspection Item, the initial 25% sample does not need to include the cold leg welds. Those welds not included in the 25% sample shall be examined prior to the end of the mitigation evaluation period if the plant is to be operated beyond that time.

TABLE 1
EXAMINATION CATEGORIES (CONT'D)

NOTES (CONT'D):

(11) Deferral of Examinations

- (a) Examinations of welds originally classified Table IWB-2500-1, Category B-J welds prior to mitigation are not permitted to be deferred to the end of the interval.
- (b) Examinations of welds classified Table IWB-2500-1, Category B-F welds, Item Numbers B5.10, and B5.20 prior to mitigation, may be deferred following weld inlay, cladding, overlay, or stress improvement, as follows:
  - (1) The first examination following weld inlay, cladding, weld overlay or stress improvement for Inspection Items E, F, J, and K may not be deferred.
  - (2) Subsequent examinations may be performed coincident with the vessel nozzle examinations required by Category B-D.
  - (3) For successive inspection intervals following weld inlay, cladding, overlay, or stress improvement, subsequent examinations may be deferred to the end of the interval, provided no additional repair/replacement activities have been performed on the examination item, and no flaws or relevant conditions requiring successive examination in accordance with Table 1 are contained in the mitigated weld.
- (c) Welds that were classified Nonmandatory Appendix R, Table R-2500-1, Examination Category R-A, Item Number R1.15 prior to mitigation shall be classified Item Number R1.20 after mitigation. Deferral of examinations shall be according to (a) and (b), above.

(12) If stress improvement (SI) techniques are used, the following shall be met:

- (a) Except as provided in (e) below, volumetric examinations shall be performed on these welds before the SI techniques are applied. The pre-SI examination shall be conducted in the same outage as the application of stress improvement or, for non-cracked welds, no more than one cycle previous to the application of SI. The examination volume of Fig. 1 applies.
- (b) Post-SI examinations are required and shall be considered the preservice baseline examination. For weld overlay used as stress improvement, the examination volume of Fig. 5(a) and the acceptance criteria of [Note (14)] applies. For other stress improvement processes, the examination volume of Fig. 1 and the following acceptance standards apply:
  - (1) For uncracked welds, no new planar surface flaws are permitted in the butt weld or base metal inside surface.
  - (2) For cracked welds, any growth or change in crack size of previously detected planar surface flaws shall be reevaluated in accordance with -3132.3.
  - (3) Flaws other than planar surface flaws detected in the butt weld or base metal inside surface, shall meet the acceptance standards of IWB-3514.
- (c) If the crack is completely removed by repair/replacement activity in accordance with IWA-4000 and stress improvement is then applied, the weld will be restored to Inspection Item D.
- (d) A documented evaluation demonstrating that the SI technique meets the performance criteria in Appendix I shall be completed.
- (e) For reactor vessel nozzle welds at cold leg temperatures requiring the core internals to be removed to perform the examination, the volumetric examinations are not required prior to application of the SI technique. If the pre-SI volumetric examination is not performed, a post-SI preservice surface examination [Note (19)] and volumetric examination shall be performed after removal of the core internals. If these examinations do not detect cracks, the weld will be considered uncracked and be subject to the examination requirements of Inspection Item D. This post-SI preservice volumetric examination must include the examination volume shown in Fig. 1. The examination volume of Fig. 1 applies in addition to the examination volume of Fig. 5(a) when weld overlay is used as stress improvement in accordance with this [Note 12(e)].

(13) Inservice Inspection for Stress Improvement

- (a) For stress improvement by weld overlay, the required examination volume of Fig. 5(a) shall be ultrasonically examined to determine if any new or existing cracks have propagated into the outer 50% of the original weld or base material or into the overlay. The angle beam shall be directed perpendicular and parallel to the piping axis, with scanning performed in four directions.
- (b) The weld overlay shall meet the inservice examination standards of IWB-3514. In applying the acceptance standards to planar indications, the thickness t_1 or t_2, defined in Fig. 5(b), shall be used as the nominal wall thickness in IWB-3514, provided the base material beneath the flaw (i.e., safe end, nozzle, or piping material) is not susceptible to PWSCC. For susceptible material, t_1 shall be used. If the acceptance standards of IWB-3514 cannot be met, the weld overlay shall meet the acceptance standards of IWB-3600. Any indication characterized as stress corrosion cracking in the weld overlay material is unacceptable.
- (c) As an alternative to (a), for inservice inspection, the weld examination volume in Fig. 1 may be ultrasonically examined. If cracking is detected extending beyond the Fig. 1 weld examination volume, the weld examination of (a) and (b) above shall be performed to determine the acceptability of the weld overlay.
- (d) For stress improvement without welding, the required examination volume of Fig. 1 shall be ultrasonically examined to determine the acceptability of the mitigated weld.
- (e) If inservice examinations of (a), (b), (c), or (d) reveal crack growth, or new cracking, meeting the acceptance standards, the weld examination volume of Fig. 1 for stress improvement without welding, or Fig. 5(a) for stress improvement by weld overlay, shall be reexamined during the first refueling outage following discovery of the crack growth or new cracking. The examination volume of Fig. 1 or Fig. 5(a), as applicable, shall be subsequently examined during each of the next two refueling outages.
- (f) If the examinations required by (e) reveal that the flaws remain essentially unchanged for three successive examinations, the weld examination schedule may revert to the sample and schedule of examinations identified in Table 1. This weld shall be included in the 25% sample.

TABLE 1
EXAMINATION CATEGORIES (CONT'D)

NOTES (CONT'D):

(14) Preservice Inspection for Weld Overlay Used as Stress Improvement

- (a) The examination volume in Fig. 5(a) shall be ultrasonically examined. The angle beam shall be directed perpendicular and parallel to the piping axis, with scanning performed in four directions, to locate and size any planar flaws that have propagated into the outer 50% of the original weld or base metal thickness or into the weld overlay. For weld overlays on cast austenitic stainless steel base materials, if 100% through-wall flaw is used for crack growth, only planar flaws that have propagated into the weld overlay or are in the overlay are required to be located and sized.
- (b) The preservice examination acceptance standards of IWB-3514 shall be met for flaws in the weld overlay material and the outer 25% of the original weld/base material. In applying the acceptance standards to planar indications, the thickness, t_1 or t_2, defined in Fig. 5(b), shall be used as the nominal wall thickness in IWB-3514, provided the base material beneath the flaw (i.e., safe end, nozzle, or piping material) is not susceptible to PWSCC. For susceptible material, t_1 shall be used. Planar flaws in the outer 25% to 50% of the original weld or base material thickness shall meet the design analysis requirements of -3132.3(d).
- (c) The flaw evaluation requirements of IWB-3640 shall not be applied to planar flaws in the weld overlay material, identified during preservice examination, that exceed the preservice examination acceptance standards of IWB-3514.

(15) If weld inlay or cladding techniques are applied, the following shall be met:

- (a) Volumetric examinations shall be performed on these welds both immediately before application of inlay or cladding and after application as a preservice baseline examination.
- (b) If the configuration of the inlay or cladding does not permit coverage in accordance with -2500(c) of the required preservice and inservice examination volume for each modified dissimilar metal weld, the weld shall be examined in accordance with Inspection Item A or B.
- (c) If the capabilities of the volumetric examination for detection, length sizing, and through-wall sizing for the dissimilar metal weld are adversely affected by the inlay or cladding, the weld shall be examined in accordance with Inspection Item A or B.
- (d) Preservice surface examinations shall be performed on the modified dissimilar metal weld after inlay or cladding application. Liquid penetrant examination in accordance with IWA-2222 or eddy current examination in accordance with IWA-2223 shall be performed. The acceptance standards of NB-5352 shall apply for the inlay or clad, except that rounded indications with dimensions larger than the smaller of $\frac{1}{16}$ in. (1.5 mm) or 50% of the thickness of the inlay or clad are unacceptable. The balance of the surface examination area shall comply with the inservice examination standards of IWB-3514.
- (e) Preservice volumetric examination shall be performed on the modified dissimilar metal weld. All flaws that were detected in (a), above, extending beyond the examination volume, shall be reexamined and sized, if they remain in the original weld. Planar flaws in the inlay or cladding shall meet the preservice examination standards of IWB-3514. Laminar flaws shall meet the acceptance standards of IWB-3514. Planar flaws in the balance of the dissimilar metal weld examination volume shall comply with the inservice examination acceptance standards of IWB-3514 or the requirements of IWB-3600.
- (f) If the crack detected prior to weld inlay or cladding is completely removed by a repair/replacement activity in accordance with IWA-4000 and the weld inlay or cladding is then applied, the weld shall be reclassified as Inspection Item G or H, respectively.

(16) Inservice Inspection Volumetric Examination for Weld Inlay or Weld Cladding

- (a) If inservice examinations reveal crack growth, or new cracking, meeting the acceptance standards of -3132.3, the weld examination volume shall be reexamined during the first refueling outage following discovery of the growth or new cracking. The weld examination volume shall be subsequently examined during each of the next two refueling outages.
- (b) Any volumetric examinations that reveal crack growth or new cracking, meeting the acceptance standards shall also be subject to a surface examination, see [Note (17)]. This surface examination shall also be required in any subsequent examinations required by (a).
- (c) If the examinations required by (a) reveal that the flaws remain essentially unchanged for three successive examinations, the weld examination schedule may revert to the sample and schedule of examinations identified in Table 1. This weld shall be included in the 25% sample population.

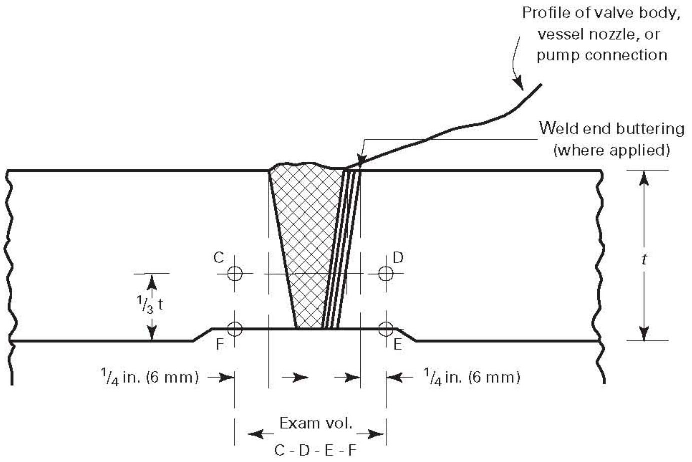
(17) *Inservice Inspection Surface Examination for Weld Inlay or Weld Cladding.* Surface examinations shall be performed on the modified dissimilar metal welds. Liquid penetrant examination in accordance with IWA-2222 or eddy current examination in accordance with IWA-2223 is required. The acceptance standards of NB-5352 apply for the inlay or clad except that rounded indications with dimensions greater than the smaller of $\frac{1}{16}$ in. (1.5 mm) or 50% of the thickness of the inlay or clad are unacceptable. The balance of the surface examination area shall comply with the inservice examination standards of IWB-3514.

(18) Volumetric examinations performed from the outside surface shall consist of a qualified Appendix VIII volumetric examination from the outside surface. If new cracking or the growth of existing cracking is detected, the additional examinations of [Note (16)] shall also be performed from the inside surface in the same outage and in subsequent outages.

(19) *Surface Examination.* Surface examinations shall be performed on these welds to determine that planar surface flaws in the butt weld inside surface are not present. For the welds to be classified as uncracked, no inside diameter surface connected planar flaws are permitted. Eddy current examination in accordance with IWA-2223 is required.

(20) *Optimized Weld Overlay.* For the purposes of this Case, processes commonly referred to as optimized weld overlay are included in Inspection Items D and E.

FIG. 1 EXAMINATION VOLUME IN WELDS NPS 2 (DN 50) OR LARGER



(2), (3), (4), (5), and (6) shall be extended to include examinations of additional welds during the current outage. The use of IWB-3514 is for the purpose of determination of scope expansion and not for the purposes of determining acceptability of the flaws. Acceptability of flaws is determined in accordance with -3132.

(1) For Table 1 Inspection Items A-1, A-2, and B and the examination volume of Fig. 1, examinations of additional unmitigated welds during the current outage are required if planar surface flaws in the butt weld or base metal inside surface exceeding the surface flaw sizes of IWB-3514 are revealed.

(2) For Table 1 Inspection Items D and E and the examination volume of Fig. 1, additional mitigated welds from the same Inspection Item and using the same stress improvement method shall be examined during the current outage if planar surface flaws in the butt weld or base metal inside surface exceeding the surface flaw sizes of IWB-3514 are revealed.

(3) For examination volumes of Figs. 2 and 5, examinations of additional weld overlays from the same Inspection Item during the current outage are required if unacceptable planar flaws are detected in the weld overlay thickness, or if this examination reveals crack growth into the examination volume larger than predicted by the previous -3132.3 analysis.

(4) For examination volumes of Figs. 3 and 4, examinations of additional mitigated welds from the same Inspection Item during the current outage are required if planar flaws exceeding the surface flaw sizes of IWB-3514 are revealed which are connected to the inlay or clad interface, if new flaws or growth of previously identified flaws are detected in the inlay or clad, or if the acceptance standards of the surface examination are not met.

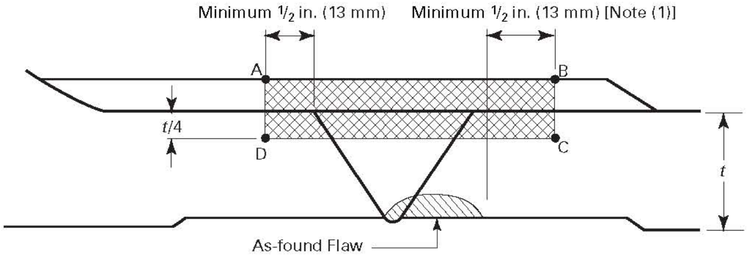
(5) Examination volumes that reveal axial crack growth beyond the specified examination volume.

(6) For other than the flaws in -2430(a)(1), (2), (3), (4), or (5), the additional examination requirements of IWB-2430 apply.

The number of additional weld examinations shall be equal to the number of welds for that Inspection Item of Table 1 originally scheduled to be performed during the present inspection period. The additional examinations shall be selected from the same Inspection Item and where applicable, from welds of similar materials, construction, and the same or higher operating temperatures. However, if the original examination was for Inspection Item B of Table 1, the additional examinations shall include first, additional welds from Inspection Item A, if any remain, and second, additional weld(s) from Inspection Item B to reach the required number of additional examinations.

(b) If the additional examinations required by -2430(a) reveal flaws exceeding the requirements of -2430(a)(1),(2), (3), (4), or (5) the examinations shall be further extended to include additional examinations during the current outage. These additional examinations shall include the remaining number of welds for that Inspection Item in Table 1, at the same or higher operating temperature conditions. In addition a 25% sample of welds of that Inspection Item at lower operating temperatures shall be sampled. If the examinations of this sample of welds at lower operating temperature reveal flaws exceeding the requirements of

FIG. 2(a) EXAMINATION VOLUME IN FULL STRUCTURAL WELD OVERLAYS



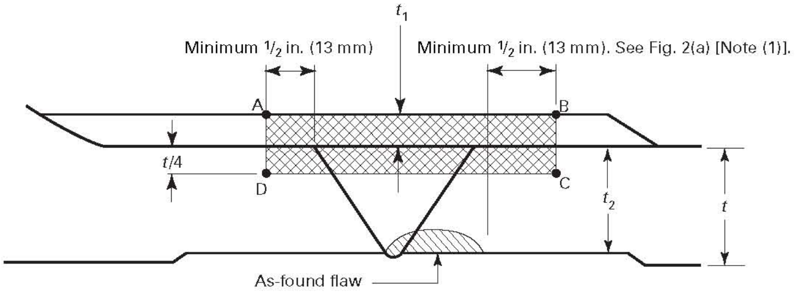
Examination Volume A–B–C–D

GENERAL NOTE: The weld includes the nozzle or safe end butter, where applied.

NOTE:

(1) For axial and circumferential flaws, the axial extent of the examination volume shall extend at least ½ in. (13 mm) beyond the as-found flaw and at least ½ in. (13 mm) beyond the toes of the original weld, including weld end butter, where applied, plus any PWSCC-susceptible base material in the nozzle and safe-end.

FIG. 2(b) DEFINITION OF THICKNESS t_1 AND t_2 FOR APPLICATION OF IWB-3514 ACCEPTANCE STANDARDS



Examination Volume A–B–C–D

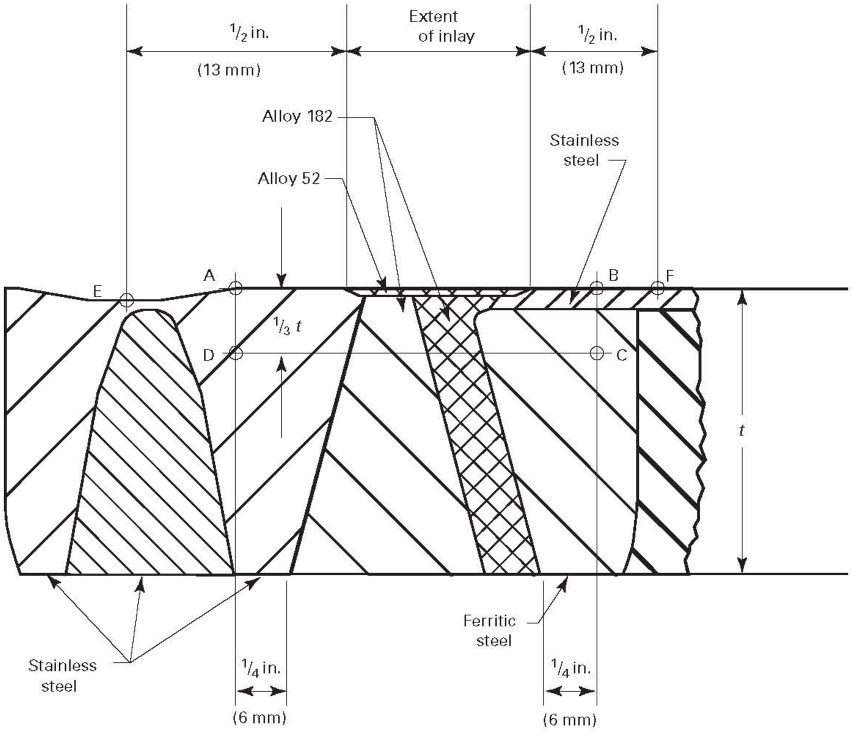
GENERAL NOTES:

(a) The nominal wall thickness is t_1 for flaws in the examination volume A-B-C-D and t_2 for flaws outside examination volume A-B-C-D.

(b) For flaws that are in examination volume A-B-C-D and extend outside this examination volume, the thickness t_1 shall be used.

(c) The weld includes the nozzle or safe end butter, where applied, plus any PWSCC-susceptible base material in the nozzle and safe-end.

FIG. 3 EXAMINATION VOLUME IN WELD INLAY



Volumetric Examination Volume A-B-C-D
Surface Examination Extent E-F

-2430(a)(1),(2), (3), (4), or (5), the examinations shall be further extended to include all welds of that Inspection Item, regardless of operating temperature, within the scope of -1100.

-2500 EXAMINATION REQUIREMENTS

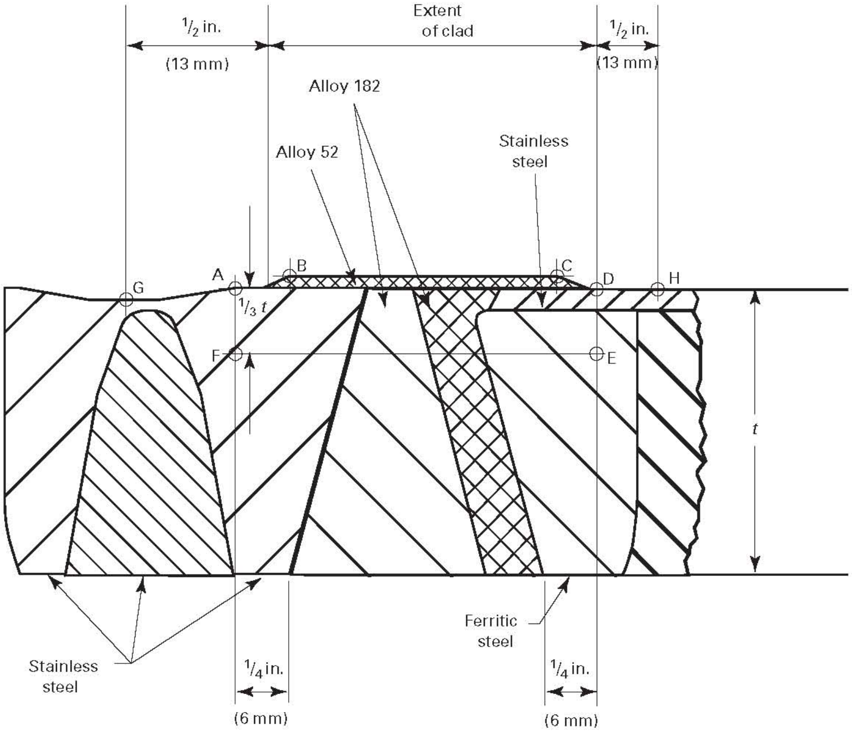
(a) Welds shall be examined as specified in Table 1. Volumetric examinations shall meet the requirements of Appendix VIII.

(b) For cast stainless steel items for which no supplement is available in Appendix VIII, the required examination volume shall be examined by Appendix VIII procedures to the maximum extent practical including 100% of the susceptible material volume (non-stainless steel volume). If 100% of the susceptible material volume is examined both before and after mitigation plus the weld overlay, inlay, or clad volume, if applicable, and no inside surface connected planar flaws are detected, the inspection frequency of Table 1 for uncracked items is applicable. If 100% of the susceptible material volume is not examined in the pre and post mitigation volumetric examinations, the inspection frequency of Table 1 for cracked items shall be applied with the following exceptions:

(1) The inspection of the mitigated weld shall not be credited to satisfy the requirement of the 25% inspection sample every inspection interval. The mitigated weld shall be inspected each inspection interval.

(2) If the required examination volume, including 100% of the susceptible material volume, is subsequently examined using a qualified ultrasonic examination and no planar flaws are detected, the weld may be placed in the 25% inspection sample population in accordance with Table 1.

FIG. 4 EXAMINATION VOLUME WELD INSIDE DIAMETER CLADDING



Volumetric Examination Volume A-B-C-D-E-F
Surface Examination Extent G-H

(c) For axial and circumferential flaws, examination shall be performed to the maximum extent practical using qualified personnel and procedures. If 100% coverage of the required volume for axial and circumferential flaws cannot be met, but essentially 100% coverage for circumferential flaws (100% of the susceptible material volume) can be achieved, the examination for axial flaws shall be completed to achieve the maximum coverage practical, with any limitations noted in the examination report. The examination coverage requirements shall be considered to be satisfied.

-3000 ACCEPTANCE STANDARDS

-3100 EVALUATION OF EXAMINATION RESULTS

-3130 INSERVICE VOLUMETRIC EXAMINATIONS

-3131 General

(a) The volumetric examinations required by -2500 and performed in accordance with IWA-2200 shall be evaluated by comparing the examination results with the acceptance standards in -3132.

(b) Volumetric examination results shall be compared with recorded results of the preservice examination and prior inservice examinations. Acceptance of welds for continued service shall be in accordance with -3132.

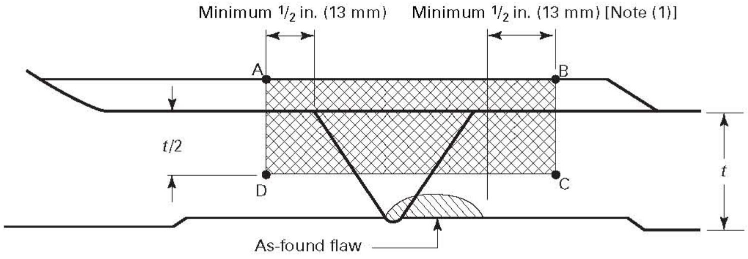
-3132 Acceptance

-3132.1 Acceptance by Volumetric Examination

(a) A weld whose volumetric examination confirms the absence of flaws shall be acceptable for continued service.

(b) A weld with planar surface flaws in the butt weld or base metal inside surface shall be accepted for continued service in accordance with the provisions of -3132.2 or

FIG. 5(a) EXAMINATION VOLUME IN WELD OVERLAYS USED AS STRESS IMPROVEMENT



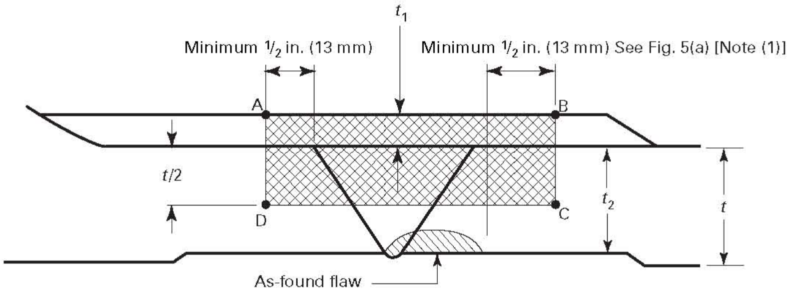
Examination Volume A–B–C–D

GENERAL NOTE: The weld includes the nozzle or safe end butter, where applied, plus any PWSCC-susceptible base material in the nozzle and safe-end.

NOTE:

(1) For axial or circumferential flaws, the axial extent of the examination volume shall extend at least ½ in. (13 mm) beyond the as found flaw and at least ½ in. (13 mm) beyond the toes of the original weld, including any weld end butter, where applied.

FIG. 5(b) DEFINITION OF THICKNESS t_1 AND t_2 FOR APPLICATION OF IWB-3514 ACCEPTANCE STANDARDS



Examination Volume A–B–C–D

GENERAL NOTES:

(a) The nominal wall thickness is t_1 for flaws in the examination volume A-B-C-D and t_2 for flaws outside examination volume A-B-C-D.

(b) For flaws that are in examination volume A-B-C-D and extend outside this examination volume, the thickness t_1 shall be used.

(c) The weld includes the nozzle or safe end butter, where applied, plus any PWSCC-susceptible base material in the nozzle and safe-end.

3132.3. Other flaws shall meet the acceptance standards of IWB-3514 or be accepted for continued service in accordance with -3132.2 or -3132.3.

(c) A weld previously mitigated by the techniques identified in Table 1 with new planar surface flaws in the butt weld or base metal inside surface or unexpected or unacceptable growth of existing flaws shall be accepted for continued service in accordance with the provisions of -3132.2 or -3132.3.

-3132.2 Acceptance by Repair/Replacement Activity or Corrective Measures

(a) A weld whose volumetric examination reveals a flaw not acceptable for continued service in accordance with the provisions of -3132.3 is unacceptable for continued service until the additional exams of -2430 are satisfied and the weld is corrected by repair/replacement activity in accordance with IWA-4000 or by corrective measures beyond the scope of this Case (e.g., stress improvement) that may result in a weld being classified as Table 1, Inspection Item E.

(b) For weld overlay examination volumes (Figs. 2 and 5) with unacceptable indications in accordance with -3132.3(d), the weld overlay shall be removed, including the original defective weld, and the weld shall be corrected by repair/replacement activity in accordance with IWA-4000.

(c) For weld examination volumes whose inside surface has been previously mitigated by weld inlay or cladding (Fig. 3 or 4, respectively), or by stress improvement without welding with unacceptable indications in accordance with -3132.3(c), the original defective weld shall be corrected by repair/replacement activity in accordance with IWA-4000.

-3132.3 Acceptance by Evaluation

(a) A weld whose volumetric examination detects planar surface flaws in the butt weld or base metal inside surface, or other flaws (-3132.1(b)) in the required examination volume that exceed the acceptance standards of IWB-3514, is acceptable for continued service if an analytical evaluation meets the requirements of IWB-3600 and the additional examinations of -2430 are performed in the current outage. The weld containing the flaw shall be reexamined in accordance with Table 1.

(b) Previously-evaluated flaws that were mitigated by the techniques identified in Table 1 need not be reevaluated nor have additional successive or additional examinations performed unless the previously evaluated flaws have grown or new planar flaws have been identified. The flaw is not considered to have grown if the size difference is within the measurement accuracy of the NDE technique employed.

(c) A weld previously mitigated by stress improvement without welding, weld inlay, or cladding, whose volumetric or surface examinations detect crack growth or new planar surface flaws in the butt weld or base metal inside surface or in the inlay or cladding, or new planar flaws or growth of previously identified planar flaws that are connected to the inlay or clad interface, is acceptable for continued service without additional repair/replacement activity if an analytical evaluation meets the requirements of IWB-3600 and the additional exams of -2430 are performed in the current outage. The mitigated weld containing the flaw shall be reexamined in accordance with Table 1.

(d) A weld overlay whose volumetric examination (Fig. 2 or 5) detects planar flaw growth or new planar flaws that exceed the acceptance standards of IWB-3514 is acceptable for continued service without repair/replacement activity if the weld overlay meets the acceptance criteria of IWB-3600, the additional exams of -2430 are performed, and the weld overlay is reexamined in accordance with Table 1. If a planar flaw is detected in the outer 25% of the original weld/base metal thickness for the examination volume of Fig. 2, or the outer 25% to 50% of the original weld or base metal thickness for the examination volume of Fig. 5, it is acceptable for continued service if the crack growth calculations and structural design and sizing calculations required for original weld overlay acceptance show or are revised to show acceptability of the detected flaw. Any indication in the weld overlay material characterized as stress corrosion cracking is unacceptable.

-3140 INSERVICE BARE METAL VISUAL EXAMINATIONS (VE)

-3141 General

(a) The bare metal visual examination (VE) required by Table 1 and performed in accordance with IWA-2200 as revised by the additional requirements of this Case shall be evaluated by comparing the examination results with the acceptance standards specified in -3142.1.

(b) Acceptance of welds for continued service shall be in accordance with -3142.

(c) Relevant conditions for the purposes of the VE shall include areas of corrosion, boric acid deposits, discoloration, and other evidence of pressure boundary leakage.

(d) In lieu of other visual examination requirements, requirements of this Case govern.

-3142 Acceptance

-3142.1 Acceptance by Bare Metal Visual Examination

(a) A weld whose VE confirms the absence of relevant conditions shall be acceptable for continued service.

(b) A weld whose VE detects a relevant condition shall be unacceptable for continued service unless the requirements of -3142.1(b)(1), (b)(2), and (b)(3) below are met.

(1) Welds with relevant conditions require further evaluation. This evaluation shall include determination of the source of the leakage and correction of the source of leakage in accordance with -3142.3.

(2) All relevant conditions shall be evaluated to determine the extent, if any, of pressure boundary degradation. The boric acid crystals and residue shall be removed to the extent necessary to allow adequate examinations and evaluation of pressure boundary degradation, and a subsequent VE of the previously-obscured surfaces shall be performed prior to return to service. Any pressure boundary degradation detected shall be evaluated to determine if any corrosion has affected the structural integrity of the component. Corrosion that has reduced component wall thickness below the thickness required by the Construction Code shall be resolved through repair/replacement activity in accordance with IWA-4000.

(3) A weld whose VE indicates relevant conditions indicative of possible through-wall leakage shall be unacceptable for continued service unless it meets the requirements of-3142.2 or -3142.3.

-3142.2 Acceptance by Supplemental Examination. A weld with relevant conditions indicative of possible through-wall leakage shall be acceptable for continued service if the results of supplemental examinations [-3200(a)] meet the requirements of -3130.

-3142.3 Acceptance by Corrective Measures or Repair/Replacement Activity

(a) A weld with relevant conditions indicative of possible through-wall leakage shall be acceptable for continued service if a repair/replacement activity corrects the condition in accordance with IWA-4000.

(b) A weld with relevant conditions not indicative of possible through-wall leakage is acceptable for continued service if the source of the relevant condition is corrected by repair/replacement activity or by corrective measures necessary to preclude pressure boundary degradation.

-3200 Supplemental Examinations

(a) Any visual examination that detects a relevant condition (-3141) indicative of possible through-wall leakage shall also receive a volumetric examination in accordance with -2500. The extent of the volumetric examination shall be in accordance with Figs. 1, 2, 3, 4, or 5, as applicable.

(b) A surface examination may also be performed to help further characterize the extent of the unacceptable condition and the need for corrective measures, analytical evaluation, or repair/replacement activity.

-9000 GLOSSARY

cladding: a corrosion resistant barrier applied on the inside diameter surface of the pipe between the Alloy 82/182 weld and the reactor coolant, not requiring excavation of some portion of the Alloy 82/182 weld.

cracked: a weld with a primary water stress corrosion cracking flaw (planar surface flaw originating from the pipe inside diameter surface of the Alloy 82/182 weld). A weld that is mitigated before it is examined shall be considered cracked.

full structural weld overlay: deposition of weld reinforcement on the outside diameter surface of the piping, component, or associated weld such that the weld reinforcement is capable of supporting the design loads without the piping, component, or associated weld lying beneath the weld reinforcement.

inlay: a corrosion resistant barrier applied on the inside diameter surface of the pipe between the Alloy 82/182 weld and the reactor coolant, requiring excavation of some portion of the Alloy 82/182 weld.

mitigation: as used in this Case, mitigation is an activity taken to reduce or eliminate the susceptibility of Alloy 82/182 weld filler material or Alloy 600[3] materials to crack initiation or crack propagation. Mitigation can be preemptive, i.e., taken before crack initiation, or repair, i.e., taken after crack initiation is discovered.

stress improvement: a process that produces sufficient compressive stress on the inside diameter wetted surface to inhibit initiation and propagation of primary water stress corrosion cracking. Stress improvement techniques with welding are a repair/replacement activity. Stress improvement techniques without welding are not included in IWA-4000 and are not a repair/replacement activity.

uncracked: a weld examined in accordance with the requirements of -2500 with no PWSCC flaws (planar surface flaw originating from the pipe inside diameter surface of the Alloy 82/182 weld) is considered uncracked in this Case.

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[3] Alloy 600 is a common abbreviation used by industry, the regulatory authority, and research organizations for UNS N06600.

MANDATORY APPENDIX I
PERFORMANCE CRITERIA AND MEASUREMENT OR QUANTIFICATION CRITERIA FOR MITIGATION BY STRESS IMPROVEMENT

I-1 PERFORMANCE CRITERIA

To minimize the likelihood of crack initiation, the process shall have resulted in a compressive stress in the susceptible material along the entire wetted surface under steady state operation. Susceptible material includes the weld, butter, and base material, as applicable. The residual stress plus normal operating stress shall be included in the evaluation.

I-1.1 Measurement or Quantification Criteria. A properly bench-marked analysis or demonstration test shall be performed to confirm the post-mitigation stress state. The analysis or testing shall show that the steady-state operating axial and hoop direction stresses combined with residual stresses are compressive at the inside surface. A pre-stress improvement residual stress condition resulting from a construction weld repair from the inside diameter to a depth of 50% of the weld thickness shall be assumed. The analysis or testing shall identify the critical process parameters and define acceptable ranges of the parameters needed to ensure that the compressive stress field has been developed.

I-2 PERFORMANCE CRITERIA

The effect produced by the mitigation process shall be permanent.

I-2.1 Measurement or Quantification Criteria. An analysis or demonstration test shall be performed to confirm that the mitigation process is permanent. The analysis and demonstration test plan shall include startup and shutdown stresses, normal operating pressure stress, thermal cyclic stresses, transient stresses, and residual stresses. The analysis or demonstration test shall account for (a) load combinations that could cause plastic ratcheting and (b) any material properties related to stress relaxation over time.

I-3 PERFORMANCE CRITERIA

The capability to perform ultrasonic examinations of the relevant volume of the component shall not have been adversely affected.

I-3.1 Measurement or Quantification Criteria. Mockup testing and nondestructive examination qualified to Section XI, Appendix VIII, performance demonstration requirements shall have been performed to demonstrate that a qualified examination of the relevant volume of the mitigated component can be accomplished subsequent to the mitigation including changes to component geometry, material properties, or other factors.

I-4 PERFORMANCE CRITERIA

The mitigation process shall not have degraded the component or adversely affected other components in the system.

I-4.1 Measurement or Quantification Criteria. An analysis shall have been performed to verify that the mitigation process does not result in changes to the piping system geometry that exceed Section III or original Construction Code design criteria. A walk down of the piping system shall be performed to verify support integrity and satisfaction of design tolerances. An analysis or evaluation shall be performed to verify that the properties specified in the material specification are met after the stress improvement.

I-5 PERFORMANCE CRITERIA

The mitigated weld shall be inspectable by a qualified process.

I-5.1 Measurement or Quantification Criteria. An evaluation shall be performed to confirm that the required examination volume of the mitigated configuration is within the scope of an Appendix VIII supplement or supplements and that the examination procedures to be used have been qualified in accordance with Appendix VIII. The evaluation shall confirm that the geometric limitations (e.g., weld crown, nozzle contour) of an Appendix VIII qualification are not exceeded for the mitigated weld.

I-6 PERFORMANCE CRITERIA

Existing flaws, if any, shall be addressed as part of the mitigation.

I-6.1 Measurement or Quantification Criteria. An examination qualified to Section XI, Appendix VIII performance demonstration requirements shall have been performed in accordance with Table 1 of this Case before the application of the mitigation process to identify and size any existing flaws. Any flaws identified shall be specifically considered in satisfying performance criterion 7.

I-7 PERFORMANCE CRITERIA

The effect of mitigation on the presence of existing flaws shall be analyzed. The stress intensity factor at the depth of the flaw shall be determined using combined residual and operating stresses, and shall be zero, indicating that the total stress is compressive at that location.

I-7.1 Measurement or Quantification Criteria. An analysis shall be performed using IWB-3600 evaluation methods and acceptance criteria to verify that the mitigation process will not cause any existing flaws to become unacceptable over the life of the weld, or before the next scheduled examination.