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WCAP-16925-NP
Revision 1

July 2009

Flaw Evaluation of CE Design RCP Suction and Discharge, and Safety Injection Nozzle Dissimilar-Metal Welds

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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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ANO	Arkansas Nuclear One
AR	aspect ratio
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing Materials
BLPB	branch-line pipe break
CE	combustion engineering
DBE	design basis earthquake
DM	dissimilar metal
EPRI	Electric Power Research Institute
FPL	Florida Power & Light
ID	inside diameter
LOCA	loss-of-coolant accident
MRP	material reliability program
NOP	normal operation
NPS	nominal pipe size
OBE	operating basis earthquake
PVNGS	Palo Verde Nuclear Generating Station
PWROG	Pressurized Water Reactor Owners Group
PWSCC	primary water stress corrosion cracking
RCP	reactor coolant pump
RPV	reactor pressure vessel
SAW	submerged arc weld
SI	safety injection
SIF	stress intensity factor
SMAW	shielded-metal arc welds
SONGS	San Onofre Nuclear Generating Station
SRSS	square root sum of squares
SSE	safe shutdown earthquake
SW	self-weight
UT	ultrasonic testing

NOMENCLATURE

a	crack depth, in.
a/t	crack depth to wall-thickness ratio
A	cross-sectional area, $in.^2$
A_i, $i = 0.3$	stress profile curve fitting coefficients
c	half crack length along surface, in.
$\frac{da}{dt}$	crack growth rate, in/hr (m/sec)
F_x	axial force component (membrane)
G_j, $i = 0.3$	G_j is SIF influence coefficient for jth stress polynomial coefficient
K	crack tip stress intensity factor, ksi$\sqrt{in}$ (MPa$\sqrt{m}$)
K_I	mode one crack tip stress intensity factor, ksi$\sqrt{in}$ (MPa$\sqrt{m}$)
ℓ	flaw length, in.
M_2	shell parameter
M_b	bending moment, in.-kip
P	internal pressure, ksi
Q	the shape factor of an elliptical crack
Q_g	thermal activation energy for crack growth, 31 kcal/mole (130 kJ/mole)
R	inside radius, in.
R	universal gas constant, 1.103×10^{-3} kcal/mole-°R (8.314×10^{-3} kJ/mole-°K)
R_m, R_o, R_i	mean radius, outside radius, and inside radius, in.
S_c	allowable bending stress for circumferentially flawed pipe, ksi
SF_b	safety factor for bending stress
SF_m	safety factor for membrane stress
T	absolute operating temperature at the location of crack, °K (°R)
t	thickness of cylinder, in.
T_{ref}	absolute reference temperature used to normalize data, 598.15°K (1076.67°R)
x	distance from the wall surface where the crack initiates, in.
Z	section modulus, $in.^3$
α	crack growth amplitude
β	crack growth exponent
β	angle to neutral axis of flawed pipe, radians
σ	stress perpendicular to the plane of the crack, ksi
σ_b	primary bending stress
σ_e	thermal expansion stress
σ_f	flow stress
σ_h	nominal hoop stress
σ_m	primary membrane stress
σ_b^c	bending stress at incipient plastic collapse
Φ	angular position of a point on the crack front
θ	one-half of the final flaw angle, radians

1 BACKGROUND AND PURPOSE

All Alloy 82/182 butt welds in Combustion Engineering (CE) plants that are exposed to temperatures equivalent to the cold leg temperatures must be volumetrically inspected by December 2010 in accordance with the American Society of Mechanical Engineers (ASME) Code Section XI (Reference 1), Appendix VIII, and Supplement 10 of Appendix VIII requirements per MRP-139 (Reference 2). 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 percent inspection coverage of Electric Power Research Institute's (EPRI) Materials Reliability Program (MRP) requirements in MRP-139 and ASME Code Appendix VIII. 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 butt welds and the smaller-diameter safety injection nozzles are exposed to nominal cold leg temperatures of 550°F, and therefore, are less susceptible to PWSCC crack initiation than nozzles in the hot leg. In addition, 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 that penetrate the pipe and obstruct the weld region. Figure 1-1 illustrates this type of obstruction. These obstructions can also make mitigation difficult, creating the need for strong technical arguments to ensure the integrity of these nozzles.

This document serves as an assessment of the flaw tolerance of the regions, using the rules of ASME Code, Section XI. The calculations in this WCAP present the maximum allowable initial flaw sizes in the DM welds and the associated PWSCC growth, both calculated for the temperatures and loadings of interest.

These allowable flaw sizes were determined for both axial and circumferential flaws, and can be used for several purposes. First, they support the argument that frequent, high-percentage (90 percent) 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.

This work also provides documented flaw evaluations of the regions of interest, in the case that 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 the CE designs that have DM welds in the region, as well as safety injection (SI) nozzles with the same dissimilar weld configurations. Participants in the program are listed in the table at the beginning of this report. To ensure coverage of all fuel cycles, the evaluations were carried out for both 18- and 24-month fuel cycles.

Since this evaluation is a feasibility study, long service times were not assessed. This avoided the need for a treatment of fatigue crack growth because PWSCC growth will be dominant for short periods. Thus, the time and cost of performing fatigue crack growth calculations are avoided until such time they are needed.

At the time revision 0 of this document was created, no non-proprietary version was needed. Therefore, a non-proprietary revision 0 was never created. A placeholder has been created in EDMS to account for the sequential numbering.

Revision 1 contains no technical changes. This revision was prepared to identify the proprietary portions of the report so that it may be submitted to the Nuclear Regulatory Commission.

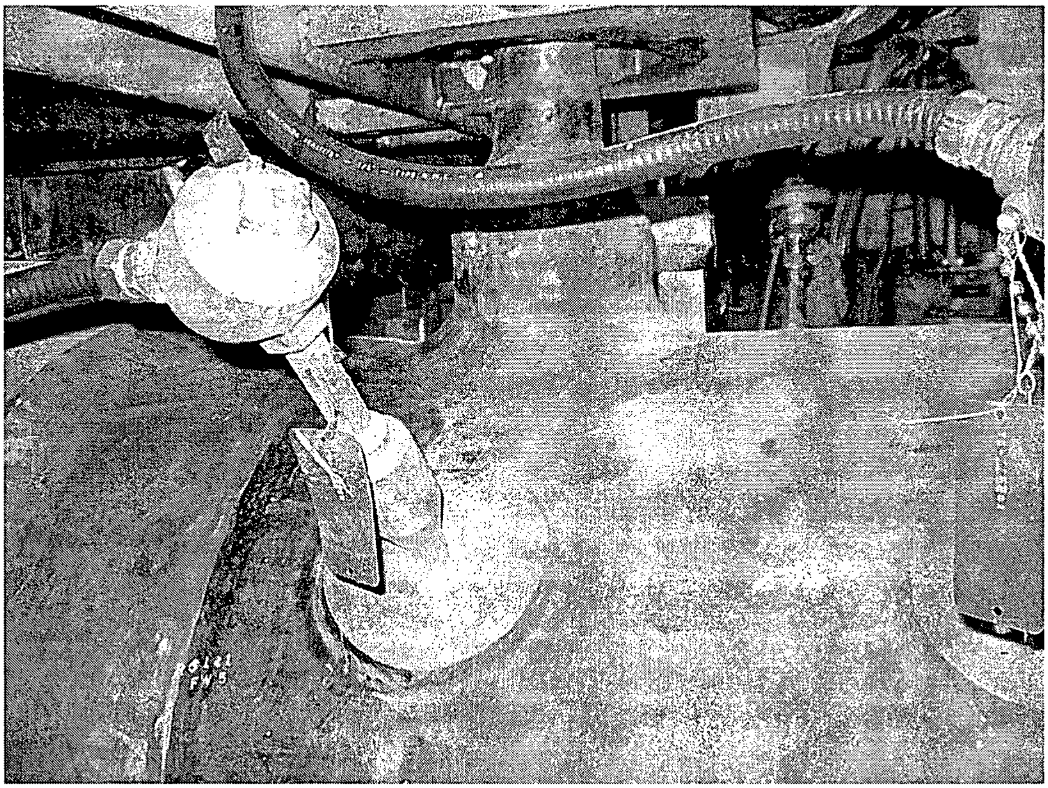

Figure 1-1 Example of Built-in Obstructions for an RCP Nozzle DM Weld

2 SUMMARY OF RESULTS AND CONCLUSIONS

A feasibility assessment was performed to determine the maximum flaw size that can be supported for periods of 18 and 24 months. The RCP suction and discharge, and the SI nozzles were chosen as the representative nozzles in the feasibility assessment. Impacts of residual stresses for both the as-welded condition and the presence of inside surface weld repairs were considered in conjunction with normal operating steady-state piping reaction loads. Operating temperatures for various CE plants were taken into consideration. Alloy weld Z-correction factors recommended by ASME were used in the analysis. Aspect ratios of 2 for axial flaws, and 6 and 10 for circumferential flaws, were assumed in the analysis.

For the RCP suction and discharge nozzles, maximum allowable initial flaw sizes for periods of 18 and 24 months were determined for various cases and are shown in Section 4. Based on the results shown in Section 4, the maximum flaw size that could be supported for a period up to 24 months was a 48 percent part through-wall inside surface axial flaw, or a 53 percent part through-wall inside surface circumferential flaw. These allowable initial flaw sizes represent a high flaw tolerance and could be greater if plant-specific conditions are taken into account.

Safety injection nozzles on Millstone Unit 2 have been mitigated already and are not a part of this investigation. Calvert Cliffs Units 1 and 2 SI nozzles have been examined and flaw evaluations performed prior to this investigation; therefore, they are not included here. Safety injection nozzles for San Onofre Nuclear Generating Station (SONGS) Units 2 and 3 and Palo Verde Units 1, 2, and 3 were not included in this study.

Safety injection nozzles including St. Lucie Units 1 and 2, ANO Unit 2, and Waterford Unit 3 were evaluated for the PWSCC crack growth in the Alloy DM welds. The initial fabrication weld residual stress and the inside surface weld repairs have significant impacts on the maximum allowable initial flaw sizes. The maximum allowable initial flaw sizes for periods of 18 and 24 months considering the impacts of inside surface weld repairs were determined and are discussed in Section 4. The results were obtained with and without inside surface repairs. For axial inside surface flaws with or without inside surface weld repairs, the allowable flaw depth for a period up to 24 months is 41 percent through-wall. For inside surface circumferential flaws, if there is no inside surface weld repair, flaw evaluation would support continual operation for a period of 24 months with a 54 percent part-through wall flaw. If inside surface weld repair is assumed, flaw evaluation would support continual operation for a period of 18 months with a 12 percent part through-wall inside flaw, and a 5.4 percent inside surface flaw for the 24-month period.

The acceptable initial inside surface flaw sizes for the nozzles of interest are summarized in Table 2-1. These were determined using the flaw evaluation procedures of Section XI of the ASME Code.

Table 2-1 Acceptable Initial Inside Surface Flaw Depth-to-Thickness Ratios with Residual and Inside Surface Weld Repair Stresses

Nozzle	Flaw Orientation	18 Months a/t (%)	24 Months a/t (%)
RCP Suction/Discharge	Axial	54	48
	Circumferential	57 to 62	53 to 59
Safety Injection	Axial	49	41
	Circumferential	12 to 22	5.4 to 11

Notes:

1. Aspect ratios of 2 for axial and 6 to 10 for circumferential flaws were considered in the analysis.
2. Results include the required margins of Section XI for Pipe Flaw Evaluation.

Recommendations

Based on the preceding feasibility assessment results, RCP suction and discharge nozzles are quite flaw tolerant, while the SI nozzles with inside surface weld repairs and high piping reaction loads show mixed results.

RCP Suction/Discharge Nozzles

The flaw tolerance is very good for all of these nozzles, indicating that the structural integrity of these regions can be maintained with less rigorous inspection requirements than those presented in the current governing industry document, MRP-139. The authors of MRP-139 have recognized this, and have inserted an option into MRP-139, Revision 1, to allow an evaluation such as that herein to be used to soften the examination requirements. It is recommended that the following items be considered and action be pursued as soon as possible to give utilities more flexibility in this area.

Safety Injection Nozzles

The existing calculations do not support the recommended actions for these nozzles in all of the plants. Therefore, the best option is to mitigate these nozzles, as there are fewer difficulties here than with the RCP nozzles.

3 CALCULATIONS

3.1 LIMITS OF APPLICABILITY

This WCAP applies to the Alloy 182/82 welds for the CE plant RCP suction and discharge nozzles, and SI nozzles with the design temperatures and Design Specification loads collected, reported, and used here for the flaw evaluation.

3.2 METHOD DISCUSSION

3.2.1 Loading Conditions

The first step is to determine the appropriate loadings for these service conditions. Both the maximum allowable end-of-evaluation-period flaw sizes and stress intensity factors are functions of the piping stresses, crack geometry, and the material properties. The maximum allowable end-of-evaluation flaw depths are determined for both axial and circumferential flaw configurations, and are used as part of the input to calculate the initial allowable flaw sizes for 18- and 24-month periods. The limit load approach used to determine the maximum allowable end-of-evaluation-period flaw depths are based on the methodology of Appendix C, Section XI of ASME Code Section XI (Reference 1). The first set of maximum allowable flaw depths is calculated using stresses from the governing normal, upset, and test conditions. The second set is calculated based on stresses for the governing emergency and faulted conditions.

The RCP suction and discharge nozzles dissimilar-metal (DM) weld and the SI nozzle DM weld regions are subject to the 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 the normal operating condition. 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, LOCA, BLPB, and accident conditions were obtained from the engineering specifications (References 15 to 23) and summarized in References 7and 14 for the RCP suction and discharge, and safety injection 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 + operating basis earthquake (NOP + OBE) represent upset load level.
3. Normal operation + safe shutdown earthquake (NOP + SSE) represent emergency load level.
4. Normal operation + accident (NOP + SSE + LOCA, NOP + SSE + BPLB, NOP + accident) represent 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 2, which is 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 the 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 are calculated using the corresponding weld geometries provided in Table 3-1, and in Table 3-2 for the SI nozzles. These stresses are bounded first within each plant, and then bounded again to obtain overall maximum values to be used as a generic candidate for the flaw evaluation. Nominal dimensions shown in Table 3-3 were then used in actual calculation of PWSCC crack growth and maximum end-of-evaluation-period flaw sizes.

Table 3-1 RCP Suction and Discharge Nozzle Geometries

Plant	Inside Diameter		Outside Diameter Safe-end (in)	Area (in^2)	Moment of Inertia (in^4)
	Safe-end (in)	Counterbore(1) (in)			
St. Lucie Unit 1	29.875	30	36.0625	314.6	2,399.2
St. Lucie Unit 2	29.75	30	36.125	318.1	2,427.0
Millstone Unit 2	29.875	30	36.0625	314.6	2,399.2
Calvert Cliffs Unit 1	29.875	30	36.0625	314.6	2,399.2
Calvert Cliffs Unit 2					
ANO Unit 2	29.75	30	36	311.0	2,371.5
Waterford Unit 3	29.75	30	36.125	318.1	2,427.0
SONGS Unit 2	29.75	30	36.125	318.1	2,427.0
SONGS Unit 3	29.75	30	36.125	318.1	2,427.0
PVNGS Unit 1	29.75	30	36.125	318.1	2,427.0
PVNGS Unit 2					
PVNGS Unit 3					

Note:

1. The counterbore dimension is at the safe-end-to-pipe weld and is used to determine weld thickness.

Table 3-2 Safety Injection Nozzle Geometries

Plant	Inside Diameter Safe-end (in)	Outside Diameter		Area (in^2)	Moment of Inertia (in^4)
		Safe-end (in)	Weld[(1)] (in)		
St. Lucie Unit 1	10.188	12.75	12.889	48.9	825.7
St. Lucie Unit 2	10.0625	12.75	12.893	51.0	853.0
Millstone Unit 2	10.188	12.75	12.889	48.9	825.7
Calvert Cliffs Unit 1	10.188	12.75	12.889	48.9	825.7
Calvert Cliffs Unit 2					
ANO Unit 2	10.188	12.75	12.889	48.9	825.7
Waterford Unit 3	10.188	12.75	12.889	48.9	825.7

Note:
1. Weld outside diameter was used for calculation.

Table 3-3 Nominal Dimensions Used for Flaw Evaluation

Parameter	Suction, Discharge (in)	Safety Injection (in)
Outside Diameter	36	12.9
Inside Diameter	30	10.2
Thickness	3	1.35

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.

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

$$\sigma_{m-tot} = \frac{F_{a-tot}}{A} \quad (3\text{-}1)$$

$$\sigma_{b-tot} = \frac{M_{b-tot}}{Z} \quad (3\text{-}2)$$

$$\sigma_e = \frac{F_{a-nop}}{A} + \frac{M_{b-nop}}{Z} \quad (3\text{-}3)$$

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
$F_{a\text{-}tot}$ = axial force due to pressure and mechanical loads
$F_{a\text{-}nop}$ = axial force due to thermal loads
$M_{b\text{-}tot}$ = bending moment across the pipe cross-section due to mechanical loads
$M_{b\text{-}nop}$ = 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 Section 3.4 of this WCAP.

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 from MRP-113 (Reference 3) are used to calculate the PWSCC crack growth. External loads, such as seismic and accident conditions, which take place for only a short duration, would not have any significant impact on the overall PWSCC growth.

3.2.2 Generation of Stress Intensity Factors (SIFs) for Surface Flaws

The stresses at the DM welds determined in Section 3.2.1 are used to determine the stress intensity factors for both the axial and circumferential surface flaw configurations. Once the stress intensity factors are determined, stress corrosion crack growth calculations (Section 3.2.3) can be performed using a PWSCC crack growth rate model developed by EPRI in Reference 5.

The bounding total stress distribution (piping plus residual stresses) was used to calculate the stress intensity factor, except as noted.

Stress Intensity Factor

The SIFs for the part through-wall longitudinal (axial) and circumferential surface cracks are calculated by using the **KCAL_PWSCC** program (References 10 and 11) based on methodology from Reference 12. For axial inside surface flaws, as shown in Figure 3-1, solutions are available in Reference 12 with cubic polynomial stress distributions across the pipe wall thickness for different flaw aspect ratios. Circumferential inside surface flaw solutions, available in Reference 12, are for pipe axial membrane stress and pipe remote bending type loads only. Reference 13 published the circumferential inside surface flaw solutions for cubic polynomial stress distributions across the pipe wall thickness and remote pipe bending moments suitable for the flaw evaluations included in this WCAP. However, axial inside surface solution options in the KCAL_PWSCC program were also used for circumferential flaws. This is considered to be either comparable or conservative when compared to the circumferential flaw solutions available in Reference 13.

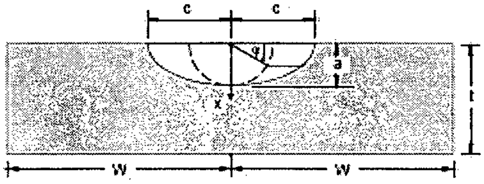

Figure 3-1 Axial Inside Surface Finite-Length Flaw in a Pipe

The stress distribution profile through the pipe wall thickness is represented by a cubic polynomial:

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

where:

A_0, A_1, A_2, and A_3 = stress profile curve fitting coefficients to be determined
x = distance from the wall surface where the crack initiates
σ = stress perpendicular to the plane of the crack

The stress intensity factor calculations for semi-elliptical surface flaws with an aspect ratio (AR) of $2c/a = 2.0$ (*c* is half-flaw length, and *a* is flaw depth) for the axial model were carried out using the expressions developed in Reference 12. For axial flaws, an aspect ratio of 2 is considered to be adequate for the expected flaw shapes in the DM welds, since any axial flaws are restricted to the width of the DM welds. For circumferential flaws, aspect ratios of 6 and 10 were considered. These are assumed to represent the realistic flaw sizes observed in the actual inspections.

The flaw solution influence coefficient at any points on the crack front can be obtained by using an interpolation method. SIF can be expressed in the general form as follows:

$$K_1 = \sqrt{\frac{\pi \alpha}{Q}} \sum_{j=0}^{3} G_j(a/c, a/t, t/R_i, \Phi) A_j a^j \qquad (3\text{-}5)$$

where:

a = crack depth, in.
c = half crack length along surface, in.
t = thickness of cylinder, in.
R_i = inside radius, in.
Φ = angular position of a point on the crack front
G_j, $i = 0.3$ = G_j is influence coefficient for jth stress distribution on crack surface
Q = the shape factor of an elliptical crack

Shape factor Q is based on the complete elliptical integral of the second kind and is approximated by:

$$Q = 1 + 1.464(a/c)^{1.65} \text{ for } a/c \leq 1 \quad (3\text{-}6a)$$

$$= 1 + 1.464(c/a)^{1.65} \text{ for } a/c > 1 \quad (3\text{-}6b)$$

For finite-length inside surface circumferential flaws, as shown in Figure 3-2, the SIF expression in Reference 13 can be used. Solutions for axial flaws from Reference 12 built into the KCAL_PWSCC program were used with aspect ratios of 6 and 10. In this case, the pipe remote stretching and maximum bending stresses are added to the through-wall stress profile to obtain the total stress distribution across the pipe wall. The stress profile was represented as a cubic polynomial.

Once the SIF has been determined, crack growth analysis of the postulated flaw in the DM welds was performed. The SIFs are calculated for all axial and circumferential surface flaws.

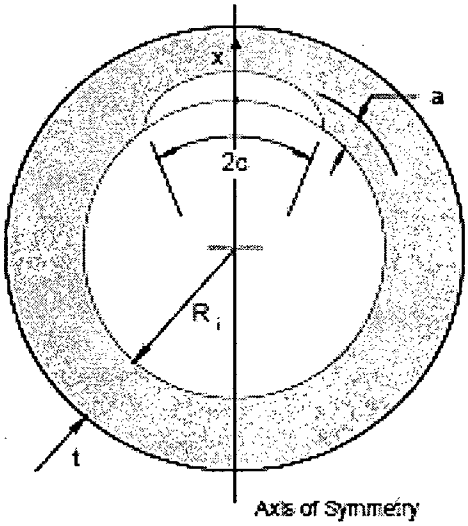

Figure 3-2 Circumferential Inside Surface Finite-Length Flaw in a Pipe as Modeled in K_I Solution

3.2.3 PWSCC Growth Rate

After the stress intensity factors are calculated, as discussed in Section 3.2.2, the crack growth calculations are performed using the PWSCC growth curve.

The recommended PWSCC growth curve for Alloy 82/182 materials is as follows (Reference 5):

$$a = exp\left[-\frac{Q_g}{R}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right) \right] \alpha(K)^{\beta} \quad (3\text{-}7)$$

where:

$\frac{da}{dt}$ = crack growth rate, m/sec (in/yr)
Q_g = thermal activation energy for crack growth, =130 kJ/mole (31 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 (1076.67°R)
α = crack growth amplitude (75th percentile),
= 1.50 x 10^{-12} at 325°C (2.47x10^{-7} at 617°F) for disposition of axial flaws
β = exponent, = 1.6
K = crack tip stress intensity factor, MPa√m, (ksi√in)

Based on an operating temperature of 549°F, the PWSCC growth rate (in m/sec) is as follows:

$$\frac{da}{dt} = 2.581 \times 10^{-13} (K)^{1.6} \qquad (3\text{-}8)$$

Here, K is expressed in MPa√m units. The PWSCC growth analysis results for circumferential and axial flaws are shown in Section 4.2 of this WCAP.

For the operating temperature range of 543°F to 553°F for all the CE plants analyzed, crack growth rate curves are given in Figure 3-4.

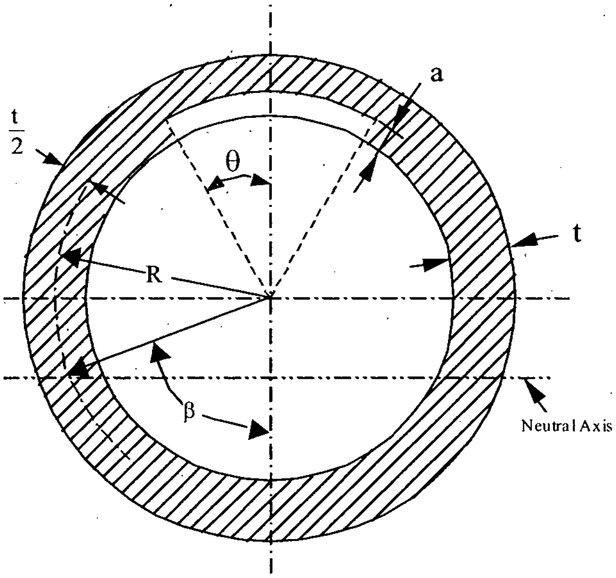

Figure 3-3 Circumferential Inside Surface Finite-Length Flaw in a Pipe for ASME Limit Load

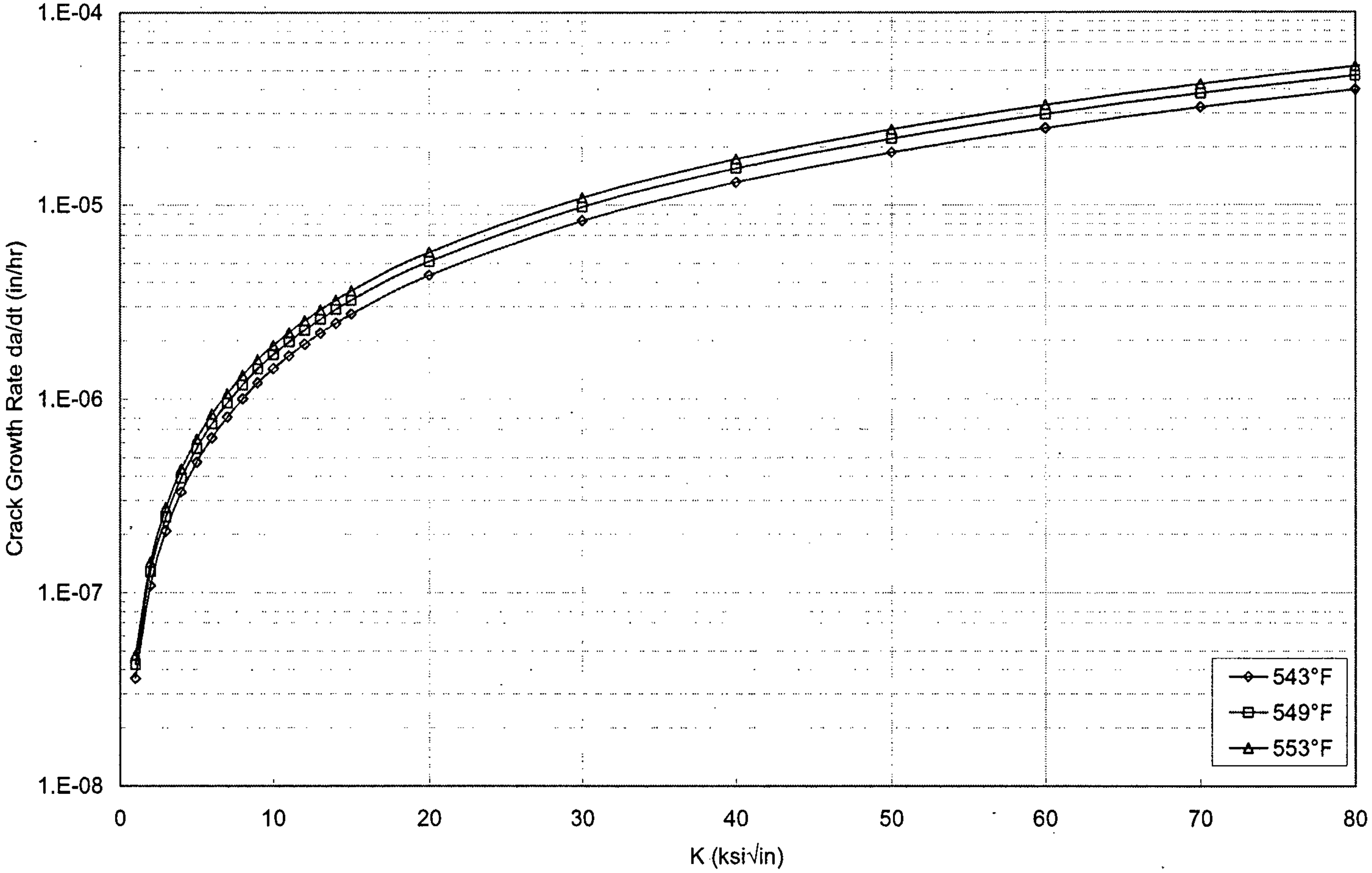

Figure 3-4 PWSCC Crack Growth Rates over the CE Plant Cold Leg Operating Temperatures

3.2.4 Maximum Allowable End-of-Evaluation-Period Flaw Size Determination

The maximum allowable end-of-evaluation-period flaw size, including a safety margin, is calculated to determine the flaw size required to cause nozzle failure due to plastic collapse. The limit load approach used is based on the methodology in Appendix C of ASME Code Section XI (Reference 1).

Circumferential Flaws

For circumferential flaws not penetrating the compressive side (Figure 3-3) of the nozzle such as $(\theta+\beta) \leq \pi$, the relation between the applied loads and flaw depth at incipient collapse is given by:

$$\sigma_b^c = \frac{2\sigma_t}{\pi}(2\sin\beta - \frac{a}{t}\sin\theta) \qquad (3\text{-}9)$$

$$\beta = \frac{1}{2}(\pi - \frac{a}{t}\theta - \pi\frac{\sigma_m}{\sigma_t}) \qquad (3\text{-}10)$$

where:

a = flaw depth, in.
t = pipe wall thickness, in.
σ_b^c = bending stress at incipient plastic collapse, ksi
θ = one-half of the final flaw angle, radians
β = angle to neutral axis of flawed pipe, radians
σ_f = flow stress is given by

$$\sigma_f = \frac{S_y + S_u}{2} \qquad (3\text{-}11)$$

where:

S_y = material yield strength, ksi
S_u = material tensile strength, ksi

For longer or continuous flaws penetrating the compressive bending region, where $(\theta+\beta)>\pi$, the relation between the applied loads and the flaw depth at incipient collapse is given by:

$$\sigma_b^c = \frac{2\sigma_f}{\pi}(2 - \frac{a}{t}\sin\beta) \qquad (3\text{-}12)$$

$$\beta = \frac{\pi}{2 - \frac{a}{t}}(1 - \frac{a}{t} - \frac{\sigma_m}{\sigma_f}) \qquad (3\text{-}13)$$

For shielded-metal arc welds (SMAW) and submerged arc welds (SAW), the allowable bending stress, S_c, is given in ASME Section XI Appendix C as follows. Code equations in Article C-6000 are used to calculate the maximum allowable end-of-evaluation-period flaw sizes for the DM welds:

$$S_c = \frac{1}{(SF_b)}\left[\frac{\sigma_b^c}{Z} - \sigma_e\right] - \sigma_m\left[1 - \frac{1}{Z(SF_m)}\right] \tag{3-14}$$

where:

S_c = allowable bending stress for circumferentially flawed pipe
σ_m = applied membrane stress due to mechanical loads
σ_e = applied total thermal expansion (membrane and bending) stress
SF_m, SF_b = safety factor for membrane and bending stresses (post-2003 version)
Z = alloy weld material correction factor for fully plastic load from Table 3-5 (References 4 and 6)

For the pipes with nominal outside diameter specification nominal pipe size (NPS) over 8 inches,

$$Z = 1.1355 + 0.0064\,(NPS) - 0.0002\,(NPS)^2 + 0.0000022\,(NPS)^3 \tag{3-15}$$

All RCP suction and discharge, and SI nozzles have NPS greater than 8 inches. Z-factors from the above equation are shown in Figure 3-5. The upper bound of the flaw depth is limited to 0.75t.

Axial Flaws

For axial flaws, the allowable flaw depth is determined by the limit load criterion using the following expression for part through-wall axial flaws:

$$\sigma_h \le \frac{\sigma_f}{(SF_m)}\left[\frac{1-\frac{a}{t}}{1-\left(\frac{a}{t}\right)/M_2}\right] \tag{3-16}$$

where:

σ_h = nominal hoop stress, ksi
M_2 = shell parameter

Hoop stress is given by Lame's equation:

$$\sigma_h = P\frac{\left(R_0^2 + R_i^2\right)}{\left(R_0^2 - R_i^2\right)} \tag{3-17}$$

where:

R_o, R_i = outside and inside radii of pipe, in.
P = internal pressure, ksi

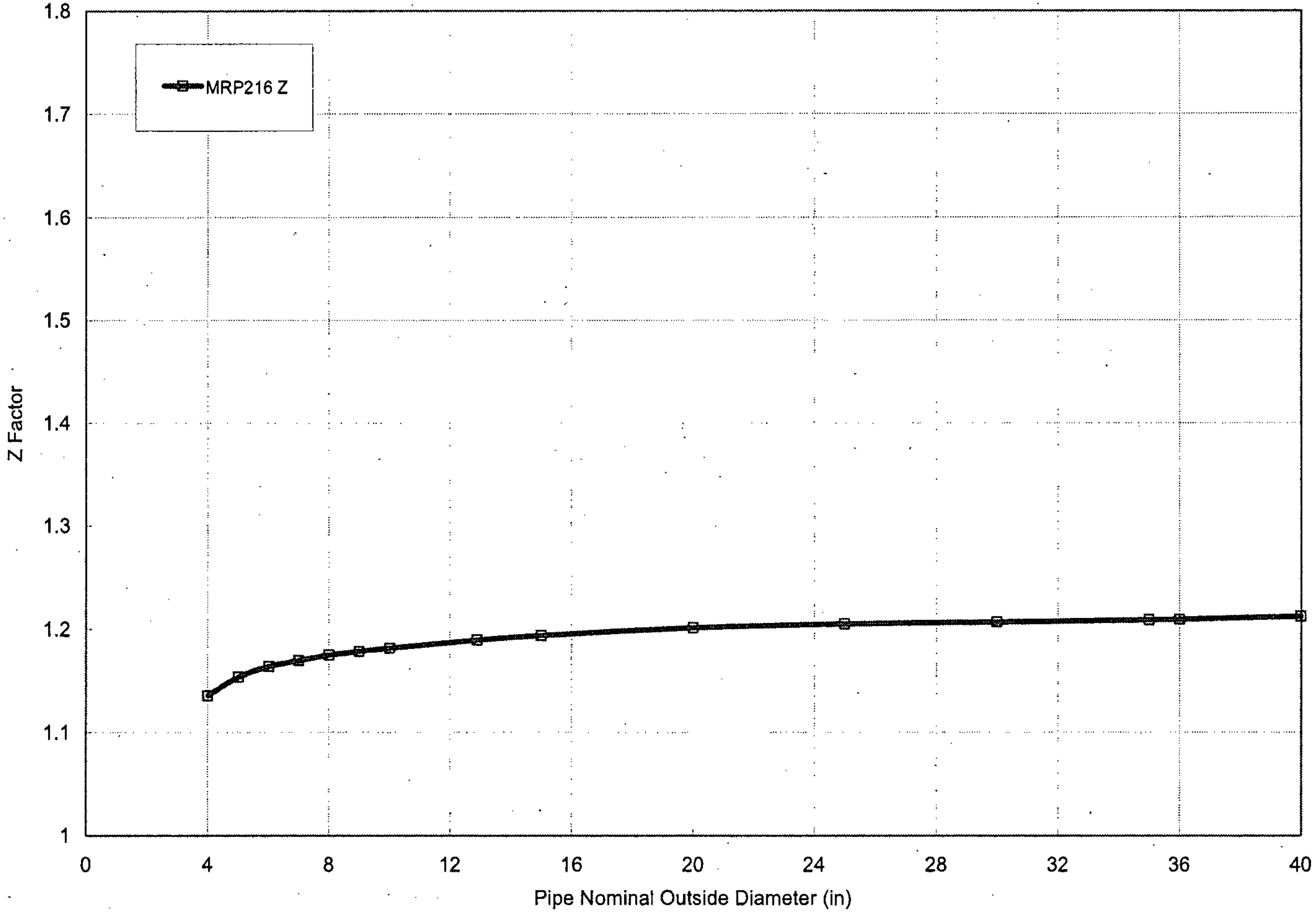

Figure 3-5 Alloy 182/82 Weld Material Correction Z-Factor for ASME Limit Load Calculation

Shell parameter M_2 is given by the equation:

$$M_2 = \sqrt{1 + \frac{1.61}{4R_m t}\ell^2} \tag{3-18}$$

where:

ℓ = flaw length, in.
R_m = mean radius, in.

The limits of applicability of the above equation are:

$$\frac{a}{t} \leq 0.75$$

and:

$$\ell < \ell_{allow} \tag{3-19}$$

where:

$$\ell_{allow} = 1.58\sqrt{R_m t}\sqrt{\left(\frac{\sigma_f}{\sigma_h}\right)^2 - \ell} \tag{3-20}$$

The maximum allowable end-of-evaluation-period flaw sizes for circumferential and axial flaws are calculated in Section 4.1 of this WCAP.

3.3 INPUT

The nominal nozzle DM weld dimensions for CE plants considered are given in Table 3-1 and Table 3-2. These dimensions were used in detailed plant-specific stress calculations. Generic dimensions in Table 3-3 were used in PWSCC crack growth and maximum end-of-evaluation-period flaw sizes. Cold leg operating temperatures of 543°F to 553°F are given in Table 3-4. Normal operating pressure is 2,250 psi. However, design pressure loading of 2,500 psi was used for all flaw evaluations.

The PWSCC crack growth rate applied to all inside surface and through-wall cracks at the Alloy 82/182 welds was obtained from Reference 5. Figure 3-4 shows the crack growth rate for the range of the CE plant cold leg operating temperatures.

Table 3-4 Plant Operating Temperatures

Utility	Plant	Temperature (°F)
Florida Power & Light	St. Lucie Unit 1	550
	St. Lucie Unit 2	
Dominion Connecticut	Millstone Unit 2	550
Constellation Energy Group	Calvert Cliffs Unit 1	548
	Calvert Cliffs Unit 2	
Arkansas Nuclear One	ANO Unit 2	553
Entergy South	Waterford Unit 3	543
Southern California Edison	SONGS Unit 2	553
	SONGS Unit 3	
Arizona Public Service	PVNGS Unit 1	556.8
	PVNGS Unit 2	
	PVNGS Unit 3	

Nozzle Loads

The nozzle loads for the RCP suction and discharge, and SI nozzles are from the Design Specifications for various CE plants considered. Loads for suction and discharge nozzles are given in Table 3-6 through Table 3-12. These loads and stresses are first enveloped for each plant; that is, for the eight pump suction and discharge nozzles. The enveloped stresses are shown in Table 3-13. For the SI nozzles, individual plant loads are shown in Table 3-14 through Table 3-17 for the four SI nozzles, enveloped loads in Table 3-18, and enveloped stresses in Table 3-19. Table 3-20 shows stresses due to internal pressure load for all the plants. The maximum representative stresses shown in Table 3-21 were used in PWSCC crack growth analysis and in Table 3-22 for the maximum end-of-evaluation-period flaw size calculation.

Table 3-5 ASME Code Section XI Required Margins for Allowable Stresses

Loading Condition	Load Level	Post-2003	
		SF_m	SF_b
Normal	A	2.7	2.3
Upset	B	2.4	2.0
Emergency	C	1.8	1.6
Faulted	D	1.3	1.4

Table 3-6 St. Lucie Units 1 and 2 Total Loads and Stresses for RCP Suction and Discharge Nozzles(1)

Forces and Moments (Reference 7)

Nozzle Location(1)	NOP		NOP+OBE		NOP+SSE	
	Force (kips)	Moment (in-kips)	Force (kips)	Moment (in-kips)	Force (kips)	Moment (in-kips)
1A2 – S	17	1,548	17	13,548	17	25,548
1A2 – D	50	4,923	50	16,923	50	28,923
1A1 – S	21	883	21	12,883	21	24,883
1A1 – D	90	3,779	90	15,779	90	27,779
1B1 – S	20	424	20	12,424	20	24,424
1B1 – D	45	4,039	45	16,039	45	28,039
1B2 – S	29	593	29	12,593	29	24,593
1B2 – D	82	1,933	82	13,933	82	25,933

Stresses

Nozzle Location(1)	NOP		NOP+OBE		NOP+SSE	
	Membrane (kips)	Bending (kips)	Membrane (kips)	Bending (kips)	Membrane (kips)	Bending (kips)
1A2 – S	0.054	0.645	0.054	5.647	0.054	10.649
1A2 – D	0.160	2.052	0.160	7.053	0.160	12.055
1A1 – S	0.067	0.368	0.067	5.369	0.067	10.371
1A1 – D	0.286	1.575	0.286	6.577	0.286	11.578
1B1 – S	0.064	0.177	0.064	5.178	0.064	10.180
1B1 – D	0.143	1.683	0.143	6.685	0.143	11.686
1B2 – S	0.092	0.247	0.092	5.249	0.092	10.250
1B2 – D	0.261	0.805	0.261	5.807	0.261	10.809

Note:
1. Designates pump number, S for suction side, and D for discharge side.

Table 3-7 Millstone Unit 2 Total Loads and Stresses(1)

Forces and Moments (Reference 7)

Nozzle Location(1)	**NOP**		**NOP+OBE**		**NOP+SSE**	
	Force (kips)	**Moment (in-kips)**	**Force (kips)**	**Moment (in-kips)**	**Force (kips)**	**Moment (in-kips)**
1A2 – S	22	330	81.8	14,166	141.80	28,002
1A2 – D	68	5,779	133.88	24,307	199.88	42,835
1A1 – S	25	468	85.3	14,304	145.30	28,140
1A1 – D	108	672	215.2	19,200	322.20	37,728
1B1 – S	15	700	74.6	14,536	134.60	28,372
1B1 – D	65	4,226	131.18	22,754	197.18	41,282
1B2 – S	19	1,126	79.4	14,962	139.40	28,798
1B2 – D	115	2,259	221.9	20,787	328.90	39,315

Stresses

Nozzle Location(1)	**NOP**		**NOP+OBE**		**NOP+SSE**	
	Membrane (ksi)	**Bending (ksi)**	**Membrane (ksi)**	**Bending (ksi)**	**Membrane (ksi)**	**Bending (ksi)**
1A2 – S	0.069	0.138	0.260	5.904	0.451	11.671
1A2 – D	0.216	2.409	0.426	10.131	0.635	17.854
1A1 – S	0.080	0.195	0.271	5.962	0.462	11.729
1A1 – D	0.344	0.280	0.684	8.003	1.024	15.725
1B1 – S	0.046	0.292	0.237	6.058	0.428	11.825
1B1 – D	0.207	1.761	0.417	9.484	0.627	17.206
1B2 – S	0.062	0.469	0.252	6.236	0.443	12.003
1B2 – D	0.365	0.941	0.705	8.664	1.046	16.386

Note:

1. Designates pump number, S for suction side, and D for discharge side.

Table 3-8 Calvert Cliffs Units 1 and 2 Total Loads and Stresses(1)

Forces and Moments (Reference 7)

Nozzle Location(1)	NOP		NOP+OBE		NOP+SSE	
	Force (kips)	Moment (in-kips)	Force (kips)	Moment (in-kips)	Force (kips)	Moment (in-kips)
1A – S	17	719	129	14,822	241	28,926
1A – D	29	2,212	245.62	19,653	462.38	37,095
1B – S	19	1,086	134	15,120	249	29,153
1B – D	58	1,443	277	15,296	496	29,149
2A – S	17	937	129	15,041	241	29,144
2A – D	29	1,562	245.62	19,003	462.38	36,445
2B – S	19	1,086	134	15,120	249	29,153
2B – D	58	1,443	277	15,296	496	29,149

Stresses

Nozzle Location(1)	NOP		NOP+OBE		NOP+SSE	
	Membrane (ksi)	Bending (ksi)	Membrane (ksi)	Bending (ksi)	Membrane (ksi)	Bending (ksi)
1A – S	0.054	0.300	0.410	6.178	0.766	12.056
1A – D	0.092	0.922	0.781	8.191	1.470	15.461
1B – S	0.060	0.453	0.426	6.302	0.792	12.151
1B – D	0.184	0.602	0.881	6.375	1.577	12.149
2A – S	0.054	0.391	0.410	6.269	0.766	12.147
2A – D	0.092	0.651	0.781	7.921	1.470	15.190
2B – S	0.060	0.453	0.426	6.302	0.792	12.151
2B – D	0.184	0.602	0.881	6.375	1.577	12.149

Note:

1. Designates pump number, S for suction side, and D for discharge side.

Table 3-9 ANO Unit 2 Total Loads and Stresses(1)

Forces and Moments (Reference 7)

Nozzle Location(1)	NOP		NOP+OBE		NOP+SSE		NOP+SSE+LOCA
	Force (kips)	Moment (in-kips)	Force (kips)	Moment (in-kips)	Force (kips)	Moment (in-kips)	Moment (in-kips)
1A – S	34	1,547	34	7,787	34	11,987	28,480
1A – D	46	4,016	46	14,336	46	21,416	34,334
1B – S	33	1,104	33	7,344	33	11,544	28,038
1B – D	84	2,180	84	12,500	84	19,580	32,498
2A – S	41	3,537	41	9,777	41	13,977	30,471
2A – D	34	4,170	34	14,490	34	21,570	34,488
2B – S	36	5,129	36	11,369	36	15,569	32,063
2B – D	72	624	72	10,944	72	18,024	30,943

Stresses

Nozzle Location(1)	NOP		NOP+OBE		NOP+SSE		NOP+SSE+LOCA
	Membrane (ksi)	Bending (ksi)	Membrane (ksi)	Bending (ksi)	Membrane (ksi)	Bending (ksi)	Bending (ksi)
1A – S	0.109	0.652	0.109	3.283	0.109	5.054	12.009
1A – D	0.147	1.693	0.147	6.045	0.147	9.030	14.478
1B – S	0.106	0.466	0.106	3.097	0.106	4.868	11.823
1B – D	0.270	0.919	0.270	5.271	0.270	8.256	13.703
2A – S	0.132	1.491	0.132	4.123	0.132	5.894	12.849
2A – D	0.108	1.758	0.108	6.110	0.108	9.096	14.543
2B – S	0.116	2.163	0.116	4.794	0.116	6.565	13.520
2B – D	0.231	0.263	0.231	4.615	0.231	7.600	13.048

Note:

1. Designates pump number, S for suction side, and D for discharge side.

Table 3-10 Waterford Unit 3 Total Loads and Stresses(1)

Forces and Moments (Reference 7)

Nozzle Location(1)	Case	NOP		NOP+OBE	NOP+SSE	NOP+SSE+BLPB
		Force (kips)	Moment (in-kips)	Moment (in-kips)	Moment (in-kips)	Moment (in-kips)
1A – S	1	-51	15,285	23,493	37,893	43,169
	2	19	1,091	9,299	23,699	28,974
	3	-47	13,534	21,742	36,142	41,418
	4	-55	17,040	25,248	39,648	44,924
	5	13	1,127	9,335	23,735	29,011
1A – D	1	124	24,650	32,858	47,258	52,534
	2	-9	51	8,259	22,659	27,935
	3	107	24,213	32,421	46,821	52,097
	4	143	25,088	33,296	47,696	52,971
	5	13	606	8,814	23,214	28,490
1B – S	1	-50	14,797	23,005	37,405	42,681
	2	19	1,091	9,299	23,699	28,975
	3	-46	13,058	21,266	35,666	40,942
	4	-54	16,538	24,746	39,146	44,422
	5	14	1,108	9,316	23,716	28,991
1B – D	1	147	23,900	32,108	46,508	51,784
	2	-10	161	8,369	22,769	28,045
	3	128	23,434	31,642	46,042	51,317
	4	167	24,369	32,577	46,977	52,253
	5	14	748	8,956	23,356	28,632
2A – S	1	-51	15,355	23,563	37,963	43,239
	2	19	1,093	9,301	23,701	28,977
	3	-48	13,602	21,810	36,210	41,485
	4	-55	17,108	25,316	39,716	44,991
	5	14	1,122	9,330	23,730	29,006
2A – D	1	124	24,658	32,866	47,266	52,541
	2	-9	52	8,260	22,660	27,935
	3	107	24,222	32,430	46,830	52,106
	4	143	25,095	33,303	47,703	52,978
	5	13	605	8,813	23,213	28,489

Table 3-10 (cont.) Waterford Unit 3 Total Loads and Stresses[(1)]

Forces and Moments (Reference 7) (cont.)

Nozzle Location[(1)]	Case	NOP Force (kips)	NOP Moment (in-kips)	NOP+OBE Moment (in-kips)	NOP+SSE Moment (in-kips)	NOP+SSE+BLPB Moment (in-kips)
2B – S	1	-50	14,829	23,037	37,437	42,713
	2	19	1,088	9,296	23,696	28,972
	3	-46	13,087	21,295	35,695	40,971
	4	-54	16,567	24,775	39,175	44,451
	5	14	1,112	9,320	23,720	28,996
2B – D	1	148	23,902	32,110	46,510	51,786
	2	-10	162	8,370	22,770	28,046
	3	128	23,436	31,644	46,044	51,320
	4	167	24,371	32,579	46,979	52,255
	5	14	749	8,957	23,357	28,633

Stresses

Nozzle Location[(1)]	Case	NOP Membrane (ksi)	NOP+OBE Bending (ksi)	NOP+SSE Bending (ksi)	NOP+SSE+BLPB Bending (ksi)	Bending (ksi)
1A – S	1	-0.160	6.298	9.680	15.613	17.787
	2	0.060	0.449	3.831	9.764	11.938
	3	-0.148	5.576	8.958	14.891	17.065
	4	-0.173	7.021	10.403	16.336	18.510
	5	0.041	0.464	3.846	9.779	11.953
1A – D	1	0.390	10.157	13.539	19.472	21.645
	2	-0.028	0.021	3.403	9.336	11.510
	3	0.335	9.976	13.358	19.291	21.465
	4	0.449	10.337	13.719	19.652	21.826
	5	0.042	0.250	3.631	9.565	11.738
1B – S	1	-0.157	6.097	9.479	15.412	17.586
	2	0.060	0.450	3.832	9.765	11.939
	3	-0.145	5.380	8.762	14.695	16.869
	4	-0.170	6.814	10.196	16.129	18.303
	5	0.044	0.456	3.838	9.771	11.945

Table 3-10 (cont.) Waterford Unit 3 Total Loads and Stresses[1]

Stresses (cont.)						
Nozzle Location[1]	**Case**	**NOP Membrane (ksi)**	**NOP+OBE Bending (ksi)**	**NOP+SSE Bending (ksi)**	**NOP+SSE+BLPB Bending (ksi)**	**Bending (ksi)**
1B – D	1	0.462	9.847	13.229	19.163	21.336
	2	-0.031	0.066	3.448	9.381	11.555
	3	0.402	9.655	13.037	18.970	21.144
	4	0.525	10.041	13.422	19.356	21.529
	5	0.044	0.308	3.690	9.623	11.797
2A – S	1	-0.160	6.327	9.709	15.642	17.815
	2	0.060	0.450	3.832	9.766	11.939
	3	-0.151	5.604	8.986	14.919	17.093
	4	-0.173	7.049	10.431	16.364	18.538
	5	0.044	0.462	3.844	9.777	11.951
2A – D	1	0.390	10.160	13.541	19.475	21.648
	2	-0.028	0.021	3.403	9.336	11.510
	3	0.335	9.980	13.362	19.295	21.469
	4	0.449	10.340	13.722	19.655	21.829
	5	0.042	0.249	3.631	9.564	11.738
2B – S	1	-0.157	6.110	9.492	15.425	17.599
	2	0.060	0.448	3.830	9.763	11.937
	3	-0.145	5.392	8.774	14.707	16.881
	4	-0.170	6.826	10.208	16.141	18.315
	5	0.044	0.458	3.840	9.773	11.947
2B – D	1	0.465	9.848	13.230	19.163	21.337
	2	-0.031	0.067	3.449	9.382	11.556
	3	0.402	9.656	13.038	18.971	21.145
	4	0.525	10.042	13.423	19.357	21.530
	5	0.044	0.309	3.690	9.624	11.797

Note:
1. Designates pump number, S for suction side, and D for discharge side.

Table 3-11 SONGS Units 2 and 3 Total Loads and Stresses[1]

Forces and Moments (Reference 7)

Nozzle Location[1]	NOP	NOP		NOP+OBE Moment (in-kips)	NOP+SSE Moment (in-kips)	NOP+SSE+LOCA Moment (in-kips)
		Force (kips)	Moment (in-kips)			
1A – S	1	-40	11,156	19,364	33,764	43,265
	2	18	848	9,056	23,456	32,957
	3	-40	11,175	19,383	33,783	43,284
	4	-39	12,700	20,908	35,308	44,809
	5	14	866	9,074	23,474	32,975
1A – D	1	107	15,219	23,427	30,471	55,424
	2	-8	1,725	9,933	16,977	41,930
	3	92	15,364	23,572	30,616	55,569
	4	113	15,477	23,685	30,729	55,682
	5	9	1,258	9,466	16,510	41,463
1B – S	1	-40	11,881	20,089	34,489	43,989
	2	18	832	9,040	23,440	32,941
	3	-41	11,093	19,301	33,701	43,201
	4	-39	12,649	20,857	35,257	44,758
	5	14	898	9,106	23,506	33,006
1B – D	1	137	14,774	22,982	30,026	54,979
	2	-10	1,560	9,768	16,812	41,765
	3	121	14,901	23,109	30,153	55,106
	4	146	15,105	23,313	30,357	55,310
	5	12	1,101	9,309	16,353	41,307
2A – S	1	-40	11,969	20,177	34,577	44,078
	2	-18	848	9,056	23,456	32,957
	3	-40	11,192	19,400	33,800	43,300
	4	-39	12,717	20,925	35,325	44,825
	5	14	866	9,074	23,474	32,975
2A – D	1	107	15,222	23,430	30,474	55,428
	2	-8	1,725	9,933	16,977	41,930
	3	92	15,345	23,553	30,597	55,550
	4	113	15,463	23,671	30,715	55,668
	5	9	1,259	9,467	16,511	41,464

Table 3-11 (cont.) SONGS Units 2 and 3 Total Loads and Stresses[1]

Forces and Moments (Reference 7) (cont.)

Nozzle Location[1]	NOP	NOP		NOP+OBE Moment (in-kips)	NOP+SSE Moment (in-kips)	NOP+SSE+LOCA Moment (in-kips)
		Force (kips)	Moment (in-kips)			
2B – S	1	-40	11,864	20,072	34,472	43,973
	2	18	832	9,040	23,440	32,941
	3	-40	11,070	19,278	33,678	43,179
	4	-39	12,612	20,820	35,220	44,721
	5	14	898	9,106	23,506	33,006
2B – D	1	137	14,776	22,984	30,028	54,981
	2	-10	1,560	9,768	16,812	41,765
	3	121	14,901	23,109	30,153	55,106
	4	146	15,093	23,301	30,345	55,298
	5	12	1,101	9,309	16,353	41,307

Stresses

Nozzle Location[1]	NOP	NOP Membrane (ksi)	NOP+OBE Bending (ksi)	NOP+SSE Bending (ksi)	NOP+SSE+LOCA Bending (ksi)	Bending (ksi)
1A – S	1	-0.126	4.597	7.979	13.912	17.826
	2	0.057	0.349	3.731	9.664	13.579
	3	-0.126	4.604	7.986	13.920	17.834
	4	-0.123	5.233	8.615	14.548	18.462
	5	0.044	0.357	3.739	9.672	13.587
1A – D	1	0.336	6.271	9.652	12.555	22.836
	2	-0.027	0.711	4.092	6.995	17.276
	3	0.289	6.330	9.712	12.615	22.896
	4	0.357	6.377	9.759	12.661	22.942
	5	0.029	0.518	3.900	6.803	17.084
1B – S	1	-0.126	4.895	8.277	14.210	18.125
	2	0.057	0.343	3.725	9.658	13.572
	3	-0.129	4.570	7.952	13.886	17.800
	4	-0.123	5.212	8.594	14.527	18.441
	5	0.044	0.370	3.752	9.685	13.599

Table 3-11 SONGS Units 2 and 3 Total Loads and Stresses(1) (cont.)

Stresses (cont.)

Nozzle Location(1)	NOP	NOP Membrane (ksi)	NOP+OBE Bending (ksi)	NOP+SSE Bending (ksi)	NOP+SSE+LOCA Bending (ksi)	Bending (ksi)
1B – D	1	0.431	6.087	9.469	12.372	22.653
	2	-0.031	0.643	4.025	6.927	17.208
	3	0.380	6.140	9.521	12.424	22.705
	4	0.459	6.224	9.605	12.508	22.789
	5	0.038	0.454	3.836	6.738	17.019
2A – S	1	-0.126	4.932	8.314	14.247	18.161
	2	-0.057	0.349	3.731	9.664	13.579
	3	-0.126	4.611	7.993	13.926	17.841
	4	-0.123	5.240	8.622	14.555	18.469
	5	0.044	0.357	3.739	9.672	13.587
2A – D	1	0.337	6.272	9.654	12.556	22.838
	2	-0.027	0.711	4.092	6.995	17.276
	3	0.289	6.323	9.704	12.607	22.888
	4	0.357	6.371	9.753	12.655	22.937
	5	0.029	0.519	3.901	6.803	17.084
2B – S	1	-0.126	4.888	8.270	14.204	18.118
	2	0.057	0.343	3.725	9.658	13.572
	3	-0.126	4.561	7.943	13.876	17.791
	4	-0.123	5.196	8.578	14.512	18.426
	5	0.044	0.370	3.752	9.685	13.599
2B – D	1	0.431	6.088	9.470	12.372	22.654
	2	-0.031	0.643	4.025	6.927	17.208
	3	0.380	6.140	9.521	12.424	22.705
	4	0.459	6.219	9.601	12.503	22.784
	5	0.038	0.454	3.836	6.738	17.019

Note:

1. Designates pump number, S for suction side, and D for discharge side.

Table 3-12 Palo Verde Units 1, 2, and 3 Loads and Stresses[1]

Nozzle Location[1]	Case	Forces and Moments (Reference 7) NOP Force (kips)	NOP+OBE Moment (in-kips)	NOP+SSE Moment (in-kips)	NOP+Accident Moment (in-kips)	Stresses NOP Membrane (ksi)	NOP+OBE Bending (ksi)	NOP+SSE Bending (ksi)	NOP+Accident Bending (ksi)
1A – S	1	58	9,643	12,043	24,643	0.183	3.973	4.962	10.153
	2	9	2,669	5,069	17,669	0.028	1.100	2.089	7.280
	3	59	10,073	12,473	25,073	0.187	4.150	5.139	10.331
	4	56	9,206	11,606	24,206	0.176	3.793	4.782	9.973
	5	4	3,688	6,088	18,688	0.014	1.520	2.509	7.700
1A – D	1	80	14,464	16,864	65,824	0.251	5.960	6.948	27.121
	2	-7	2,852	5,252	54,212	-0.021	1.175	2.164	22.337
	3	75	14,247	16,647	65,607	0.237	5.870	6.859	27.032
	4	85	14,683	17,083	66,043	0.267	6.050	7.039	27.211
	5	10	3,010	5,410	54,370	0.031	1.240	2.229	22.402
1B – S	1	58	9,643	12,043	61,003	0.183	3.973	4.962	25.135
	2	9	2,669	5,069	54,029	0.028	1.100	2.089	22.261
	3	59	10,073	12,473	61,433	0.187	4.150	5.139	25.312
	4	56	9,206	11,606	60,566	0.176	3.793	4.782	24.955
	5	4	3,688	6,088	55,048	0.014	1.520	2.509	22.681
1B – D	1	68	14,199	16,599	65,559	0.213	5.850	6.839	27.012
	2	-6	2,855	5,255	54,215	-0.020	1.176	2.165	22.338
	3	64	13,987	16,387	65,347	0.200	5.763	6.752	26.925
	4	73	14,414	16,814	65,774	0.228	5.939	6.928	27.101
	5	9	2,997	5,397	54,357	0.029	1.235	2.224	22.396

Table 3-12 (cont.) Palo Verde Units 1, 2, and 3 Loads and Stresses(1)

Nozzle Location(1)	Case	Forces and Moments (Reference 7)				Stresses			
		NOP Force (kips)	NOP+OBE Moment (in-kips)	NOP+SSE Moment (in-kips)	NOP+Accident Moment (in-kips)	NOP Membrane (ksi)	NOP+OBE Bending (ksi)	NOP+SSE Bending (ksi)	NOP+Accident Bending (ksi)
2A – S	1	58	9,643	12,043	61,003	0.183	3.973	4.962	25.135
	2	9	2,669	5,069	54,029	0.028	1.100	2.089	22.261
	3	59	10,073	12,473	61,433	0.187	4.150	5.139	25.312
	4	56	9,206	11,606	60,566	0.176	3.793	4.782	24.955
	5	4	3,688	6,088	55,048	0.014	1.520	2.509	22.681
2A – D	1	68	14,199	16,599	65,559	0.213	5.850	6.839	27.012
	2	-6	2,855	5,255	54,215	-0.020	1.176	2.165	22.338
	3	64	13,987	16,387	65,347	0.200	5.763	6.752	26.925
	4	73	14,414	16,814	65,774	0.228	5.939	6.928	27.101
	5	9	2,997	5,397	54,357	0.029	1.235	2.224	22.396
2B – S	1	58	9,643	12,043	61,003	0.183	3.973	4.962	25.135
	2	9	2,669	5,069	54,029	0.028	1.100	2.089	22.261
	3	59	10,073	12,473	61,433	0.187	4.150	5.139	25.312
	4	56	9,206	11,606	60,566	0.176	3.793	4.782	24.955
	5	4	3,688	6,088	55,048	0.014	1.520	2.509	22.681
2B – D	1	68	14,199	16,599	65,559	0.213	5.850	6.839	27.012
	2	-6	2,855	5,255	54,215	-0.020	1.176	2.165	22.338
	3	64	13,987	16,387	65,347	0.200	5.763	6.752	26.925
	4	73	14,414	16,814	65,774	0.228	5.939	6.928	27.101
	5	9	2,997	5,397	54,357	0.029	1.235	2.224	22.396

Note:

1. Designates pump number, S for suction side, and D for discharge side.

Table 3-13 Bounding Stresses for Pump Suction and Discharge Nozzles(1)

Plant	NOP		NOP+OBE		NOP+SSE		NOP+SSE+LOCA Bending (ksi)	NOP+Accident Bending (ksi)
	Membrane (ksi)	Bending (ksi)	Membrane (ksi)	Bending (ksi)	Membrane (ksi)	Bending (ksi)		
FPL1	0.286	2.052	0.286	7.053	0.286	12.055	–	–
FPL2								
DCM2	0.365	2.409	0.705	10.131	1.046	17.854	–	–
CEG 1 & 2	0.184	0.922	0.881	8.191	1.577	15.461	–	–
ANO2	0.270	2.163	0.270	6.110	0.270	9.096	14.543	–
W3	0.525	10.340	0.525	13.722	0.525	19.655	21.829	–
SONGS 2	0.459	6.377	0.459	9.759	–	14.555	22.942	–
SONGS 3								
APS 1, 2, & 3	0.228	–	0.228	6.050	–	7.039	–	27.211

Note:

1. Designates pump number, S for suction side, and D for discharge side. Stresses due to internal pressure and residual stresses are added to these stresses to obtain total stresses.

Table 3-14 St. Lucie Unit 1 Safety Injection Nozzle Loads(1) (Reference 7)

Load Condition	Axial Force	Bending Moment
RCP 1A2		
NOP	0.440	84.856
NOP + DBE	4.776	266.832
NOP + SSE	9.111	448.807
NOP + SSE + Accident	-28.866	627.524
RCP 1A1		
NOP	0.703	122.079
NOP + DBE	3.617	253.538
NOP + SSE	6.530	384.996
NOP + SSE + Accident	6.627	702.138
RCP 1B1		
NOP	0.917	315.980
NOP + DBE	5.279	586.881
NOP + SSE	9.641	857.782
NOP + SSE + Accident	-14.570	1,577.038
RCP 1B2		
NOP	1.090	287.073
NOP + DBE	6.111	565.192
NOP + SSE	11.133	843.312
NOP + SSE + Accident	-3.593	1,382.324
Envelope		
NOP	1.090	316.0
NOP + DBE	6.111	586.9
NOP + SSE	11.133	857.8
NOP + SSE + Accident	28.866	1,577.0

Note:

1. Stresses due to internal pressure and residual stresses are added to these stresses to obtain total stresses.

Table 3-15 St. Lucie Unit 2 Safety Injection Nozzle Loads(1) (Reference 7)

Load Condition	Axial Force	Bending Moment
RCP 2A2		
NOP	6.423	705.943
Upset/Emergency	19.867	1,522.434
Faulted	25.234	2,405.074
RCP 2A1		
Normal Thermal + Self-weight	10.307	840.275
Accident Thermal + Self-weight	-3.777	1,540.276
NOP + DBE	15.932	1,209.645
NOP + SSE	14.244	2,219.276
RCP 2B1		
Normal Thermal + Self-weight	0.752	413.339
Accident Thermal + Self-weight	-2.886	1,143.789
NOP + DBE	4.110	718.874
NOP + SSE	7.717	1,533.972
RCP 2B2		
Normal Thermal + Self-weight	-3.041	154.879
Accident Thermal + Self-weight	-4.307	638.415
NOP + DBE	5.669	377.694
NOP + SSE	8.735	1,011.022
Envelope		
Normal Thermal + Self-weight	10.307	840.3
Accident Thermal + Self-weight	4.307	1,540.3
NOP + DBE	15.932	1,209.6
NOP + SSE		

Note:
1. Stresses due to internal pressure and residual stresses are added to these stresses to obtain total stresses.

Table 3-16 ANO Unit 2 Safety Injection Nozzle Loads(1) (Reference 7)

Load Condition	Axial Force	Bending Moment
RCP 1A		
NOP	28.470	702.383
NOP + DBE	41.212	1,496.578
NOP + SSE	48.332	1,845.285
NOP + SSE + Accident	69.848	2,633.706
RCP 1B		
NOP	9.119	766.893
NOP + DBE	20.867	1,281.494
NOP + SSE	23.426	1,443.162
NOP + SSE + Accident	48.137	2,464.280
RCP 2A		
NOP	8.073	712.330
NOP + DBE	21.786	1,324.370
NOP + SSE	28.011	1,635.574
NOP + SSE + Accident	49.488	2,522.346
RCP 2B		
NOP	27.933	1,015.446
NOP + DBE	38.715	1,781.190
NOP + SSE	48.921	2,050.236
NOP + SSE + Accident	69.864	2,884.823
Envelope		
NOP	28.470	1,015.4
NOP + DBE	41.212	1,781.2
NOP + SSE	48.921	2,050.2
NOP + SSE + Accident	69.864	2,884.8

Note:

1. Stresses due to internal pressure and residual stresses are added to these stresses to obtain total stresses.

Table 3-17 Waterford Unit 3 Safety Injection Nozzle Loads(1) (Reference 7)

Load Condition	Axial Force	Bending Moment
RCP 1A		
Thermal Stratification	-17.007	1,713.778
NOP	-21.087	1,774.634
NOP + DBE	22.184	1,850.446
NOP + SSE	23.281	1,926.257
NOP + SSE + Accident	35.504	2,536.719
RCP 1B		
Thermal Stratification	-3.944	267.556
NOP	-9.317	609.659
NOP + DBE	11.087	857.028
NOP + SSE	12.856	1,104.397
NOP + SSE + Accident	27.992	1,547.161
RCP 2A		
Thermal Stratification	2.935	505.837
NOP	1.594	714.455
NOP + DBE	4.300	885.234
NOP + SSE	7.006	1,056.013
NOP + SSE + Accident	16.666	1,493.447
RCP 2B		
Thermal Stratification	6.244	864.261
NOP	9.935	1,395.395
NOP + DBE	11.694	1,478.954
NOP + SSE	13.453	1,562.513
NOP + SSE + Accident	26.416	1,871.921
Envelope		
Thermal Stratification	17.007	1,713.8
NOP	21.087	1,774.6
NOP + DBE	22.184	1,850.4
NOP + SSE	23.281	1,926.3
NOP + SSE + Accident	35.504	2,536.7

Note:
1. Stresses due to internal pressure and residual stresses are added to these stresses to obtain total stresses.

Table 3-18 Enveloped Loads for Safety Injection Nozzles[1]

Plant	NOP		NOP+OBE		NOP + SSE		NOP + Accident	
	Force (kips)	**Moment (in-kips)**	**Force (kips)**	**Moment (in-kips)**	**Force (kips)**	**Moment (in-kips)**	**Force (kips)**	**Moment (in-kips)**
FPL1	1.1	316.0	6.1	586.9	11.133	857.782	28.866	1,577.038
FPL2	10.3	840.3	15.9	1,209.6	14.244	2,219.276	14.244	2,219.276
DCM2	–	–	–	–	–	–	–	–
CEG 1 & 2	–	–	–	–	–	–	–	–
ANO2	28.5	1,015.4	41.2	1,781.2	48.921	2,050.236	69.864	2,884.8
W3	21.1	1,774.6	22.2	1,850.4	23.281	1,926.257	35.504	2,536.7

Note:

1. Stresses due to internal pressure and residual stresses are added to these stresses to obtain total stresses.

Table 3-19 Enveloped Stresses for Safety Injection Nozzles[1]

Plant	NOP		NOP+OBE		NOP + SSE		NOP + Accident	
	Membrane (ksi)	**Bending (ksi)**	**Membrane (ksi)**	**Bending (ksi)**	**Membrane (ksi)**	**Bending (ksi)**	**Membrane (ksi)**	**Bending (ksi)**
FPL1	0.022	2.466	0.125	4.580	0.227	6.695	0.590	12.308
FPL2	0.206	6.454	0.319	9.292	0.285	17.047	0.285	17.047
DCM2	–	–	–	–	–	–	–	–
CEG 1 & 2	–	–	–	–	–	–	–	–
ANO2	0.582	7.925	0.842	13.902	0.999	16.001	1.427	22.515
W3	0.431	13.850	0.453	14.442	0.476	15.034	0.725	19.798

Note:
1. Stresses due to internal pressure and residual stresses are added to these stresses to obtain total stresses.

Table 3-20 Stresses Due to Internal Pressure Load

Plant	Suction/Discharge		Safety Injection	
	Hoop (ksi)	Axial (ksi)	Hoop (ksi)	Axial (ksi)
St. Lucie Unit 1	13.736	5.618	10.828	4.164
St. Lucie Unit 2	13.611	5.555	10.557	4.028
Millstone Unit 2	13.736	5.618	10.828	4.164
Calvert Cliffs Unit 1	13.736	5.618	10.828	4.164
Calvert Cliffs Unit 2				
ANO Unit 2	13.864	5.682	10.828	4.164
Waterford Unit 3	13.611	5.555	10.828	4.164
SONGS Unit 2	13.611	5.555	10.476	3.988
SONGS Unit 3				
PVNGS Unit 1	13.611	5.555	9.421	3.460
PVNGS Unit 2				
PVNGS Unit 3				
Envelope	13.864	5.682	10.828	4.164

Table 3-21 Normal Operation Pipe Axial Stresses used in PWSCC Analysis for Circumferential Flaws(1)

Nozzle	Stresses	
	σ_m (ksi)	σ_b (ksi)
Pump Suction and Discharge	0.525	10.340
Safety Injection	0.582	19.048

Note:
1. Axial pressure stresses and residual stresses are added to these to obtain total applied stresses.

Table 3-22 Upset and Faulted Load Level Axial Stresses used in End-of-Evaluation-Period Flaw Sizes for Circumferential Flaws(1)

Nozzle	Upset		Faulted	
	σ_m (ksi)	σ_b (ksi)	σ_m (ksi)	σ_b (ksi)
Suction and Discharge	0.881	13.722	1.577	27.211
Safety Injection	0.842	25.166	0.999	31.284

Note:
1. Axial pressure stresses are added to these to obtain total applied stresses.

Residual Stresses

The axial and hoop residual stresses used in this evaluation are from MRP-113 (Reference 3). The residual stresses were combined with the normal operating steady-state nozzle loads to obtain the total through-wall stress distributions used in the PWSCC crack growth analysis. The MRP-113 report provides a set of residual stresses with and without inside diameter (ID) repair on the Alloy 82/182 butt welds for a typical RPV discharge nozzle, a typical pressurizer surge nozzle, and a typical pressurizer safety nozzle. Sensitivity studies to determine the effects of various residual stress profiles on the PWSCC crack growth results are shown in Section 4.2 of this WCAP. The residual stresses without ID repair are digitized and tabulated in Table 3-23, while the residual stresses with the ID repair are shown in Table 3-24.

Table 3-23 Fabrication Weld Residual Stresses without ID Weld Repair[1]

Normalized Through-Wall Distance from ID	RPV Discharge[2]		Surge Nozzle[3]		Safety Nozzle[3]	
	Hoop (ksi)	Axial (ksi)	Hoop (ksi)	Axial (ksi)	Hoop (ksi)	Axial (ksi)
0.00	20.83	28.14	10.29	19.76	-7.00	42.00
0.05	2.31	-6.11	-0.96	4.38	-11.39	35.89
0.10	-7.75	-27.61	-11.39	-10.41	-38.56	-6.30
0.15	-8.81	-39.56	-18.25	-26.03	-55.30	-45.21
0.20	7.86	-34.78	-18.52	-35.89	-42.68	-46.85
0.25	14.22	-28.67	-11.94	-36.44	-32.80	-46.30
0.30	11.04	-22.04	-11.11	-27.40	-26.48	-38.63
0.35	16.60	-16.46	-10.02	-20.55	-16.88	-32.05
0.40	15.27	-15.13	-7.55	-16.71	-12.21	-25.48
0.45	19.77	-10.09	-5.35	-14.25	-10.02	-18.90
0.50	19.85	-10.35	-0.14	-12.60	-2.33	-14.52
0.55	24.60	-6.11	4.53	-10.41	-1.78	-12.05
0.60	26.19	-4.25	11.94	-7.67	11.66	-6.03
0.65	32.79	1.33	19.90	-3.56	11.39	-6.03
0.70	40.98	10.35	30.87	7.40	31.97	9.32
0.75	55.25	28.14	41.58	23.01	43.50	23.84
0.80	55.51	36.90	49.26	30.68	46.24	31.51
0.85	56.83	37.17	51.73	32.88	49.26	34.52
0.90	58.42	35.58	53.65	33.97	50.36	34.52
0.95	60.36	31.33	55.03	32.88	53.10	34.79
1.00	60.63	23.63	56.00	31.50	56.00	31.50

Notes:

1. Residual stresses are from EPRI MRP-113 (Reference 3).
2. Residual stress profile is applicable to the CE plant suction and discharge nozzles due to similarity in nozzle weld geometry.
3. Bounding residual stress profile from the surge and safety nozzle is applicable to the CE plant safety injection nozzles.

Table 3-24 Fabrication Weld Residual Stresses with ID Weld Repair(1)

Normalized Through-Wall Distance from Inside Surface	RPV Discharge(2)		Surge Nozzle(3)		Safety Nozzle(3)	
	Hoop (ksi)	Axial (ksi)	Hoop (ksi)	Axial (ksi)	Hoop (ksi)	Axial (ksi)
0.00	62.49	47.14	59.16	51.00	59.16	47.00
0.05	63.03	49.56	58.79	50.33	59.16	47.32
0.10	63.57	50.10	58.79	49.58	60.28	48.08
0.15	65.72	47.41	58.42	47.70	59.53	48.83
0.20	59.53	21.28	58.05	42.07	59.16	48.08
0.25	46.87	-2.42	56.19	31.17	54.70	33.05
0.30	30.44	-29.36	46.14	15.77	41.67	22.16
0.35	10.24	-49.02	38.33	2.63	39.44	16.90
0.40	0.27	-56.30	35.72	-6.76	44.28	12.77
0.45	3.23	-56.03	32.37	-15.77	40.93	3.76
0.50	7.81	-52.53	18.23	-31.55	32.74	-13.90
0.55	16.97	-45.52	4.47	-49.95	8.93	-38.31
0.60	23.97	-36.09	4.09	-50.33	1.12	-44.32
0.65	34.75	-22.09	7.07	-49.20	-2.60	-49.58
0.70	44.18	-5.93	17.12	-38.31	15.63	-39.44
0.75	53.06	15.35	33.49	-21.41	29.77	-26.29
0.80	53.06	27.74	45.77	-8.64	38.70	-15.40
0.85	53.06	32.05	50.98	1.88	43.91	-9.39
0.90	54.41	34.48	51.72	10.89	44.65	-4.88
0.95	56.30	35.56	51.72	15.40	43.91	-2.63
1.00	60.00	33.13	51.72	20.00	44.65	-3.00

Notes:

1. Residual stresses are from EPRI MRP-113 (Reference 3).
2. Residual stress profile is applicable to the St. Lucie Units 1 and 2 RCP suction and discharge nozzles due to similarity in nozzle weld geometry.
3. Bounding residual stress profile from the surge and safety nozzle is applicable to the St. Lucie Units 1 and 2 safety injection nozzles.

For the RCP suction and discharge nozzle, the through-wall residual stress distributions were approximated by those for the reactor vessel nozzle shown in MRP-113 due to similarity in the nozzle sizes. For the SI nozzles, bounding through-wall residual stress distributions from both the surge and the safety nozzles shown in MRP-113 were used in the feasibility assessment. For sensitivity study purposes, surge nozzle axial residual stress distribution was also used for the SI nozzle circumferential crack growth feasibility assessment, since the geometries of both the SI nozzle and the surge nozzle are similar.

The applicable residual stress profiles to be used for the CE RCP suction and discharge nozzles are shown in Figure 3-6 for hoop direction, and in Figure 3-7 for axial direction, while the corresponding stresses for the SI nozzles are shown in Figure 3-8 and Figure 3-9.

Material Properties

The material properties used in the DM weld region are based on the yield and ultimate strength of Alloy 82/182 at 550°F (Reference 0). This is an acceptable assumption because the actual normal operating temperatures for CE plant cold leg DM welds are in the narrow range of 543°F to 553°F. A yield strength of 30.1 ksi and an ultimate strength of 80 ksi were used for the material flow stress calculation.

Maximum Allowable End-of-Evaluation-Period Flaw Size

In order to determine the end-of-evaluation-period flaw sizes as discussed in Section 3.2.4, the nozzle geometry, material properties, and applicable nozzle loads are required as inputs. The nozzle geometry at the weld location is shown in Table 3-3.

For the axial maximum allowable end-of-evaluation-period flaw size evaluations, a design pressure of 2,500 psi is used to calculate the limiting flaw size at each nozzle.

For circumferential maximum allowable end-of-evaluation-period flaw size calculation for the pump suction and discharge nozzles, the nozzle loads used are tabulated in Table 3-22.

Figure 3-6 Residual Stresses without ID Weld Repair for RCP Suction and Discharge Nozzles

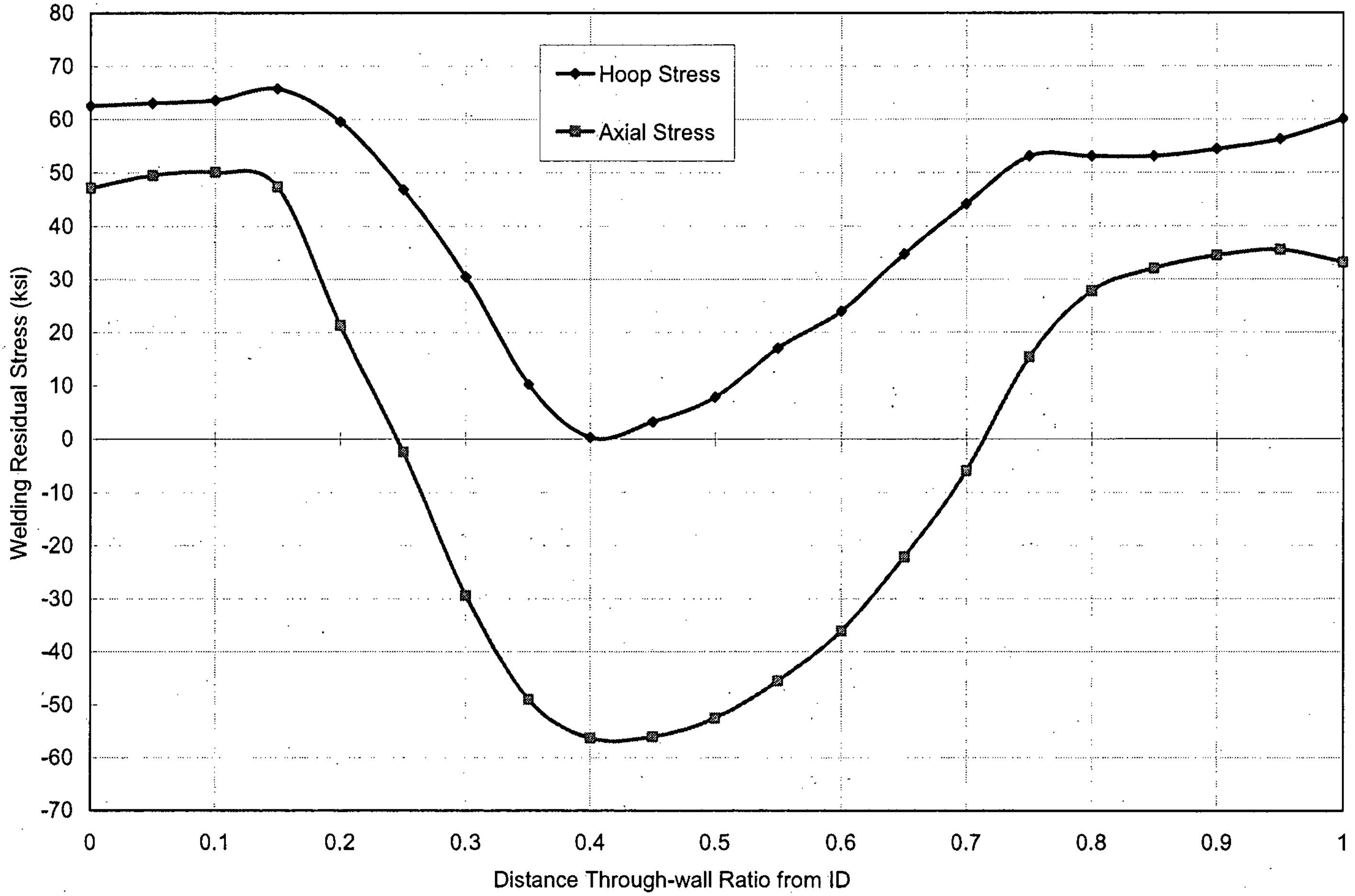

Figure 3-7 Residual Stresses with ID Weld Repair for RCP Suction and Discharge Nozzles

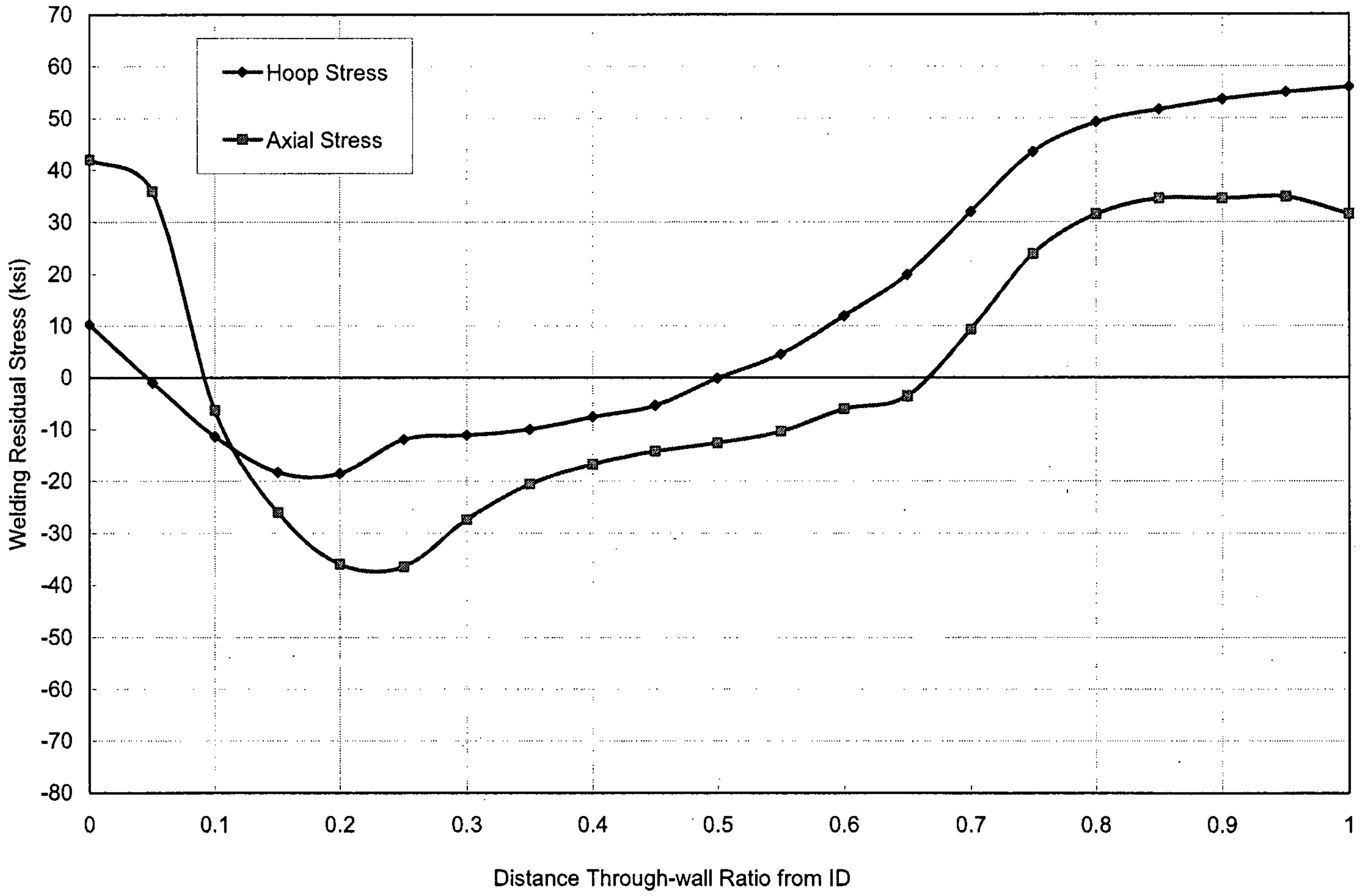

Figure 3-8 Residual Stresses without ID Weld Repair Used for the SI Nozzle DM Weld Region

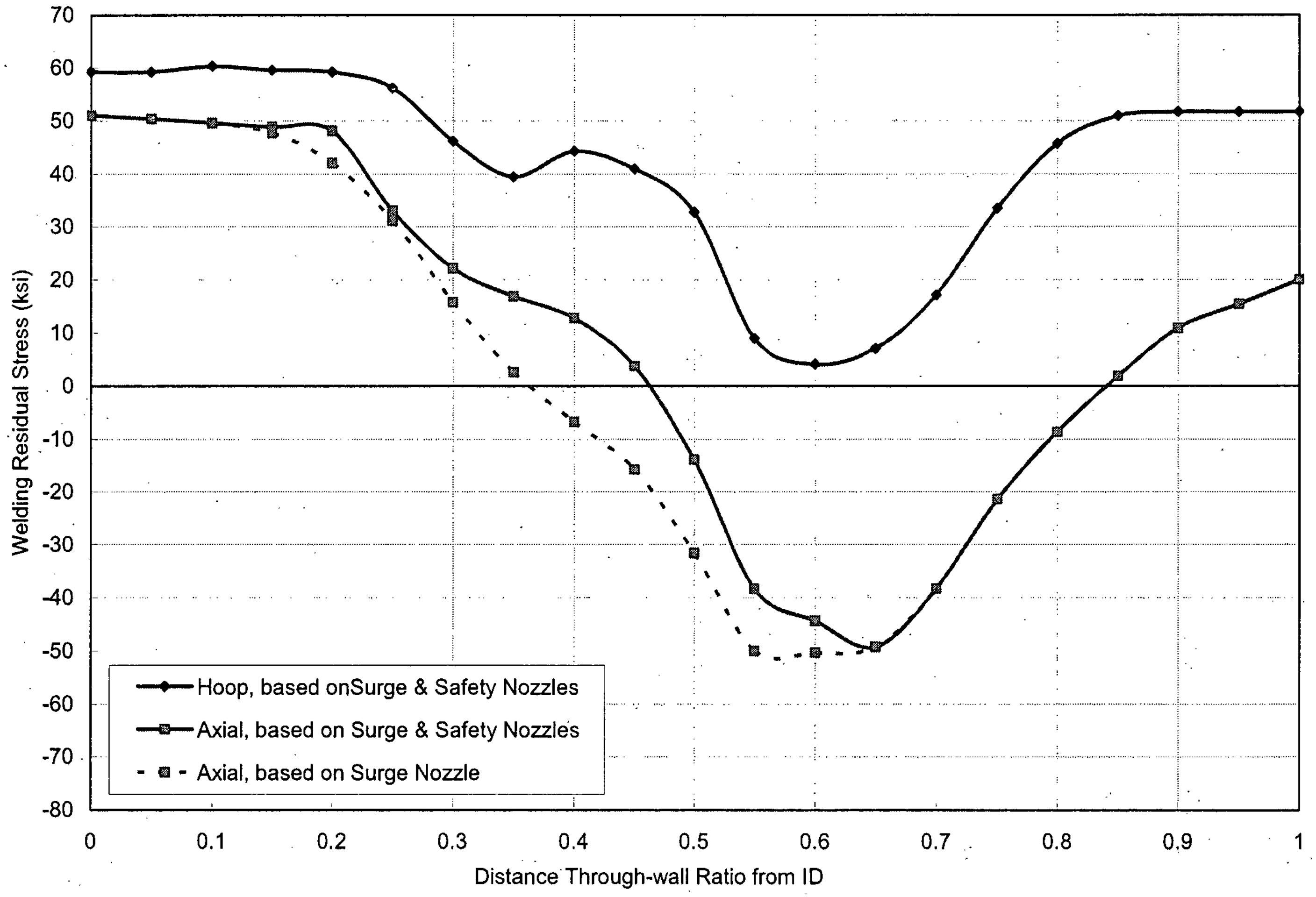

Figure 3-9 **Residual Stresses with ID Weld Repair Used for the SI Nozzle DM Weld Region**

4 EVALUATIONS, ANALYSIS, DETAILED CALCULATIONS, AND RESULTS

4.1 MAXIMUM ALLOWABLE END-OF-EVALUATION-PERIOD FLAW SIZE

The maximum allowable end-of-evaluation-period flaw size calculation is performed in accordance with the evaluation procedure and acceptance criteria given in IWB-3640 and Appendix C of ASME Code Section XI. This methodology is based on limit load solution for plastic collapse failure mode for austenitic alloys such as Alloy 82/182. The methodology is described in Section 3.2.4 of this WCAP; both the maximum circumferential and axial allowable end-of-evaluation-period flaw sizes are determined based on the equations shown in that section. The maximum allowable end-of-evaluation-period flaw size evaluation for axial and circumferential flaws incorporated all the CE plants considered. All the loads were first bounded within each plant, and then bounded over all the plants. Stresses were calculated for each pump nozzle based on its geometry, and then the maximum stress level within each plant was selected to represent that plant. Z-factors for the Alloy 82/182 welds, as implemented in the 2009 Addenda of Section XI, IWB 3640, were considered in the limit load or limit bending stress calculations. The maximum allowable end-of-evaluation-period flaw sizes were determined based on the most limiting stress condition from normal/upset and emergency/faulted conditions as discussed in Section 3.2.1.

Axial Flaws

For axial flaws, an aspect ratio (flaw length/flaw depth) of 2 is considered adequate to represent the expected flaw shape in the DM weld regions for the nozzles of interest. A pressure loading of 2,500 psi is the only loading used to calculate the maximum allowable end-of-evaluation-period axial flaw sizes. The maximum hoop stress listed in Table 3-20 was used in the calculation. The material property values for Alloy 82/182 weld used in the calculation is documented in Section 3.4, while the nozzle geometry used is obtained from Table 3-1.

Maximum allowable end-of-evaluation-period axial flaw sizes calculated for the Alloy 82/182 welds for the suction and discharge, and SI nozzles using the ASME Code equations show that they all exceed the Code limit of 75 percent of the wall thicknesses. Therefore, they are limited to 75 percent of the DM weld thickness per ASME Code Section XI, Article IWB-3640, as shown in Table 4-1.

Table 4-1 End-of-Evaluation-Period Maximum Allowable Inside Surface Flaw Sizes

Flaw Orientation	Flaw Aspect Ratio 2c/a	Normal/Upset		Emergency/Faulted	
		Suction/Discharge a/t	SI a/t	Suction/Discharge a/t	SI a/t
Axial	2	0.75	0.75	0.75	0.75
Circumferential	6	0.75	0.75	0.75	0.75
	10	0.75	0.75	0.73	0.66

Circumferential Flaws

For circumferential flaws, aspect ratios of 6 and 10 were assumed and the maximum allowable end-of-evaluation-period circumferential flaw sizes were calculated. The bounding stresses for all the CE plants, as listed in Table 3-22 for the pump suction and discharge, and SI nozzles, are used in the calculation. It should be noted that the self-weight is considered small; normal operation loads are assumed to represent the thermal expansion; combined upset, emergency, and faulted loads are the total applied piping loads; and the difference in the total load and the normal operation loads are the additional loads over the normal operation in the ASME Code, Section XI, Appendix C Criteria. The circumferential maximum allowable end-of-evaluation-period flaw sizes for all the CE plants are tabulated in Table 4-1. These flaw sizes are used to determine the maximum allowable initial flaw sizes that support continued plant operation for a specific period of time based on the PWSCC crack growth analysis results.

4.2 PWSCC CRACK GROWTH ANALYSIS AND RESULTS

Detailed PWSCC crack growth evaluations at normal operating loads were performed to obtain the final flaw sizes at the end of 18- and 24-month periods. The enveloped normal operation piping hoop stress listed in Table 3-20 was used for the axial flaws. Enveloped axial piping stresses in Table 3-21 were used in the circumferential flaw growth analysis. These normal operation piping stresses are superposed over the corresponding internal pressure stresses.

[

]$^{a, c, e}$

The computed crack tip SIFs for various flaw depths are shown in Figure 4-5 for axial flaws in suction and discharge nozzles, and in Figure 4-6 for SI nozzles. Figure 4-7 shows SIFs for circumferential flaws in suction and discharge nozzles. Figure 4-8 shows SIFs for circumferential flaws in the SI nozzles.

[

]$^{a, c, e}$

Crack growth analysis results for axial flaws in suction/discharge nozzles are shown in Figure 4-9, and in Figure 4-10 for SI nozzles. Corresponding results for circumferential flaws in suction/discharge nozzles and SI nozzles are shown in Figure 4-11 and Figure 4-12, respectively. These figures show the results for the cases without fabrication residual stresses, with weld residual stresses, and with ID weld repair residual stresses. Figure 4-9 through Figure 4-12 also illustrate the limiting maximum allowable end-of-evaluation-period flaw size computed from the ASME Code. The combination of flaw growth and the maximum allowable flaw sizes from these figures is used to estimate the maximum allowable initial flaw sizes for the 18- and 24-month periods. These initial flaw sizes are listed in Table 4-2 as a ratio of wall thickness. This table illustrates that all the suction and discharge nozzles have adequate allowable initial flaw depths with a minimum of 48 percent of the wall thickness for a 24-month operating period.
SI nozzles also have adequate initial flaw axial sizes with a minimum of 37 percent for the case without residual stress or weld repair, for a 24-month operating period. For the case with ID weld repair, the allowable initial flaw depth is reduced and ranges from 5.4 percent to 12 percent for a 24- and 18-month operating period, respectively.

Table 4-2 Maximum Allowable Initial Flaw Sizes

a,c,e

a,c,e

Figure 4-1 Total Hoop Stress with ID Weld Repair at Normal Operation for Suction/Discharge Nozzles

a,c,e

Figure 4-2 Total Axial Stress with ID Weld Repair at Normal Operation for Suction/Discharge Nozzles

a,c,e

Figure 4-3 Total Hoop Stress with ID Weld Repair at Normal Operation Used for SI Nozzle

a,c,e

Figure 4-4 **Total Axial Stress with ID Weld Repair at Normal Operation Used for SI Nozzle**

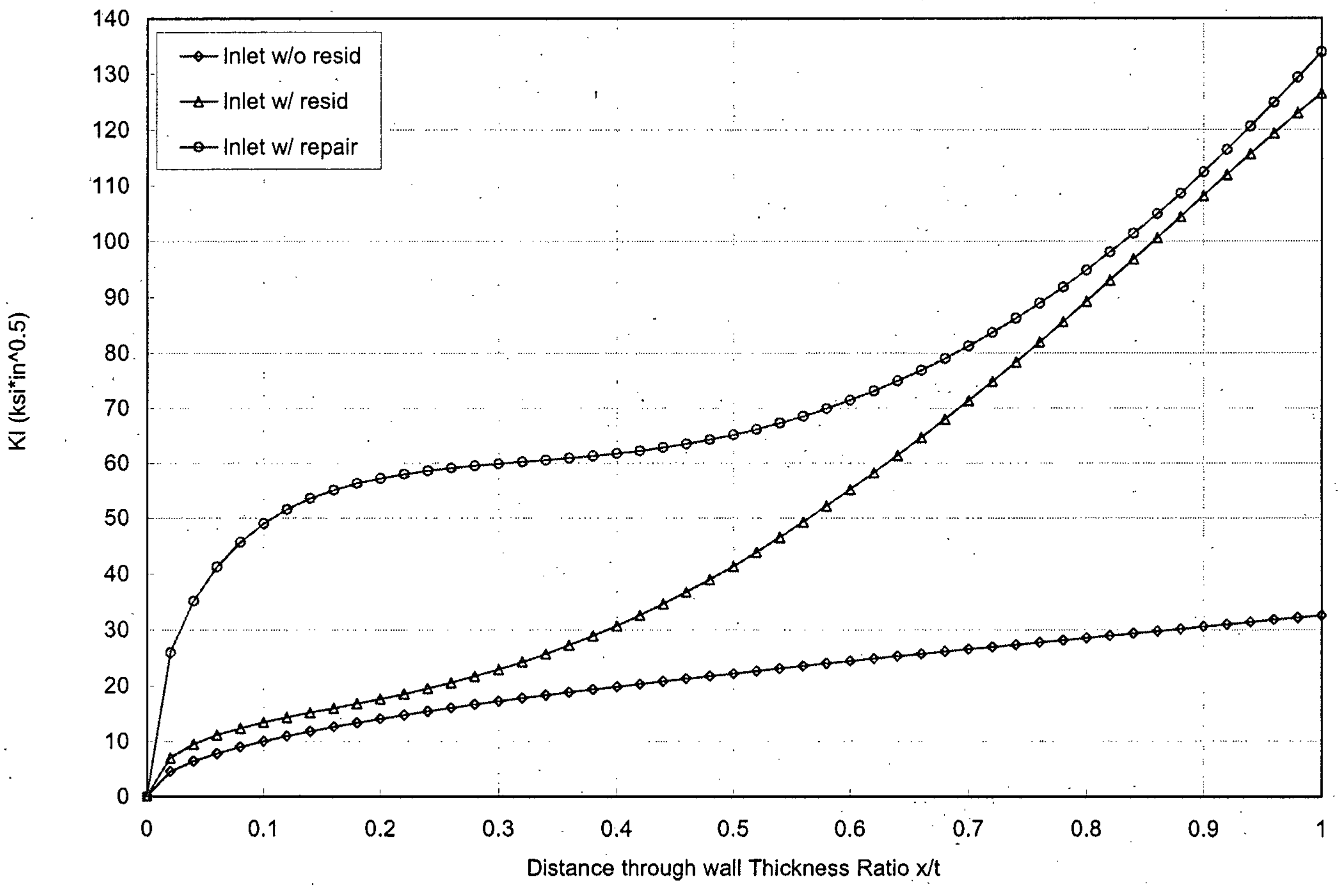

Figure 4-5 Stress Intensity Factors for Axial Flaws in RCP Suction/Discharge Nozzles

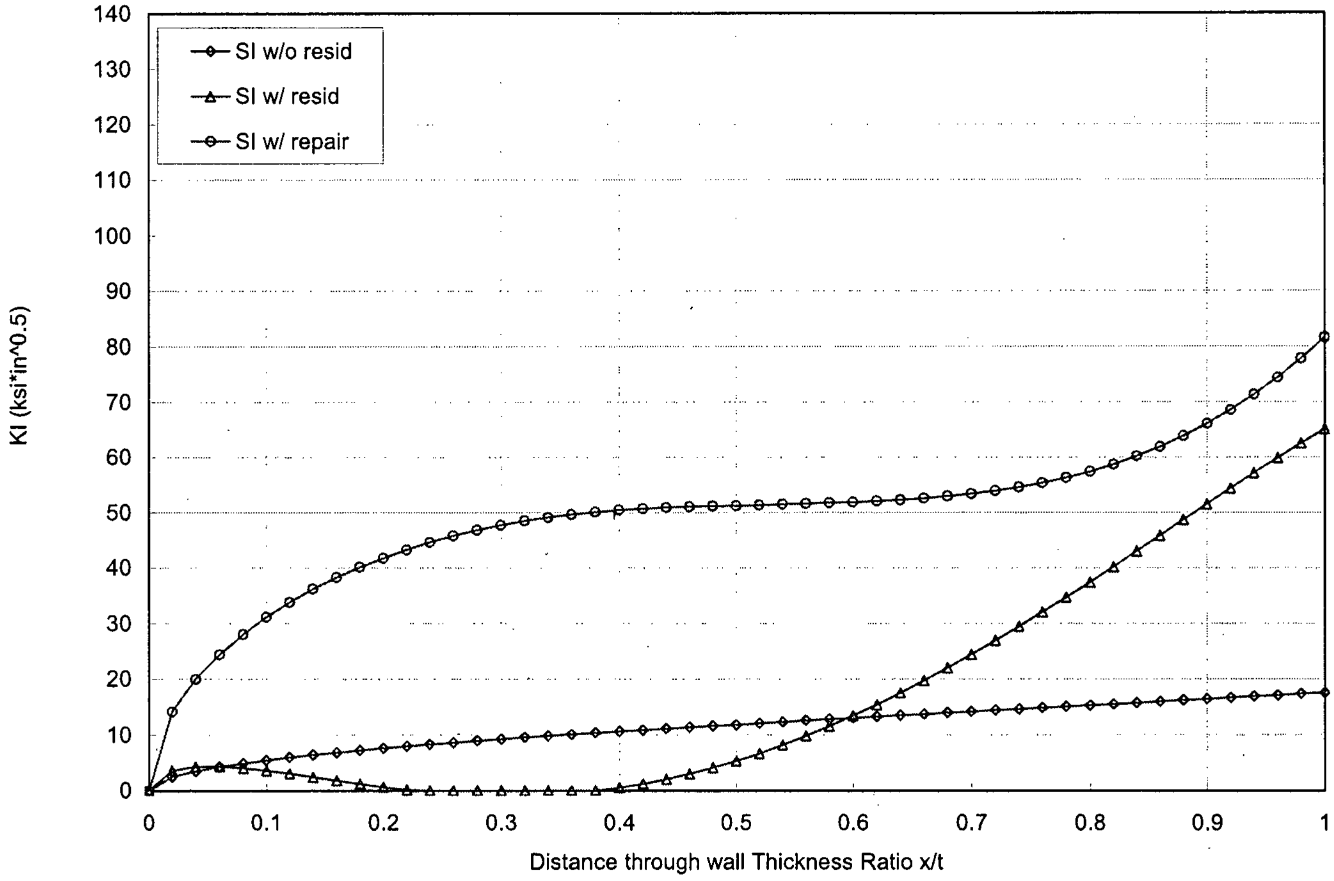

Figure 4-6 Stress Intensity Factors for Axial Flaw in SI Nozzles

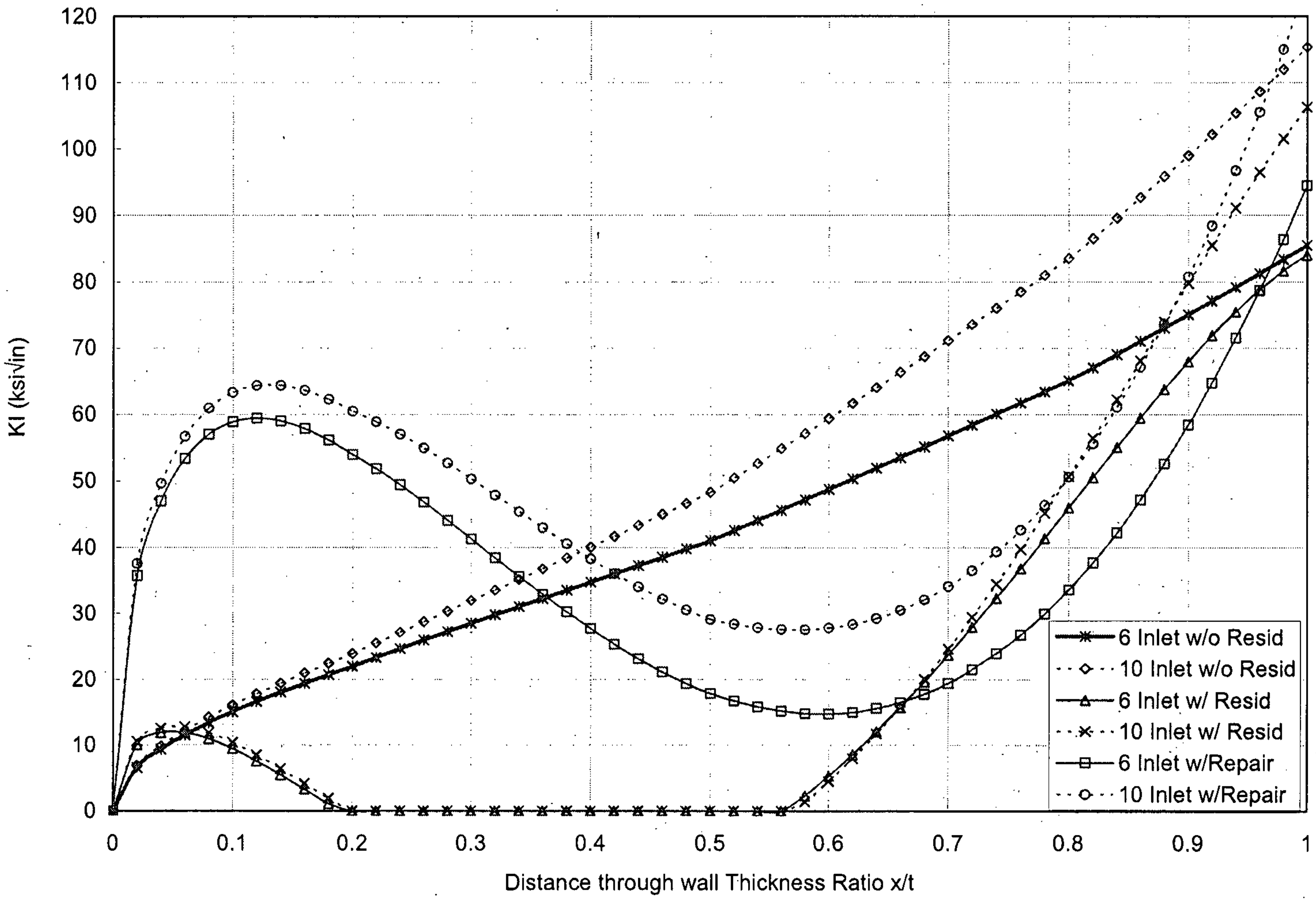

Figure 4-7 Stress Intensity Factors for Circumferential Flaw in Suction/Discharge Nozzles

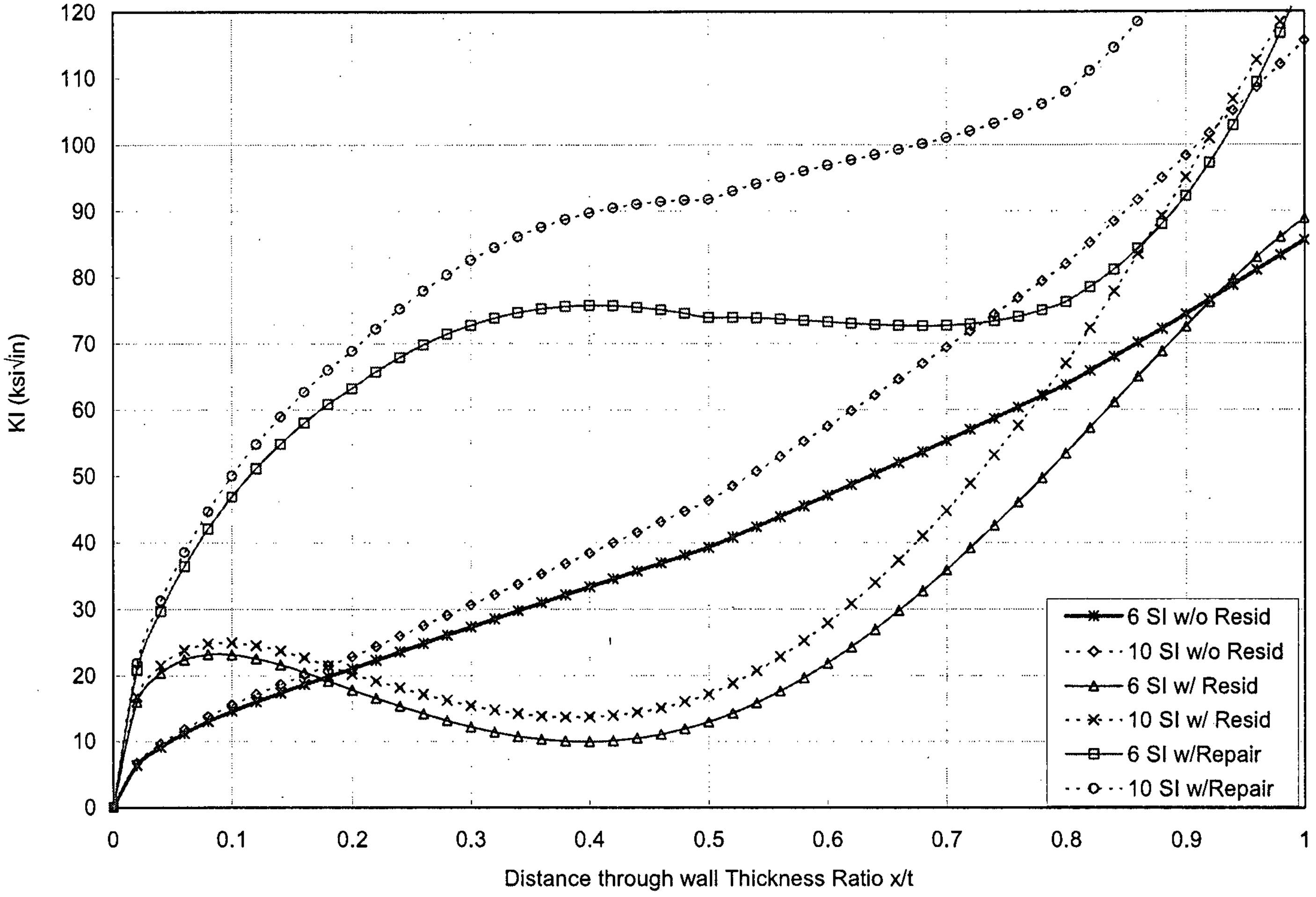

Figure 4-8 Stress Intensity Factors for Circumferential Flaw in SI Nozzles

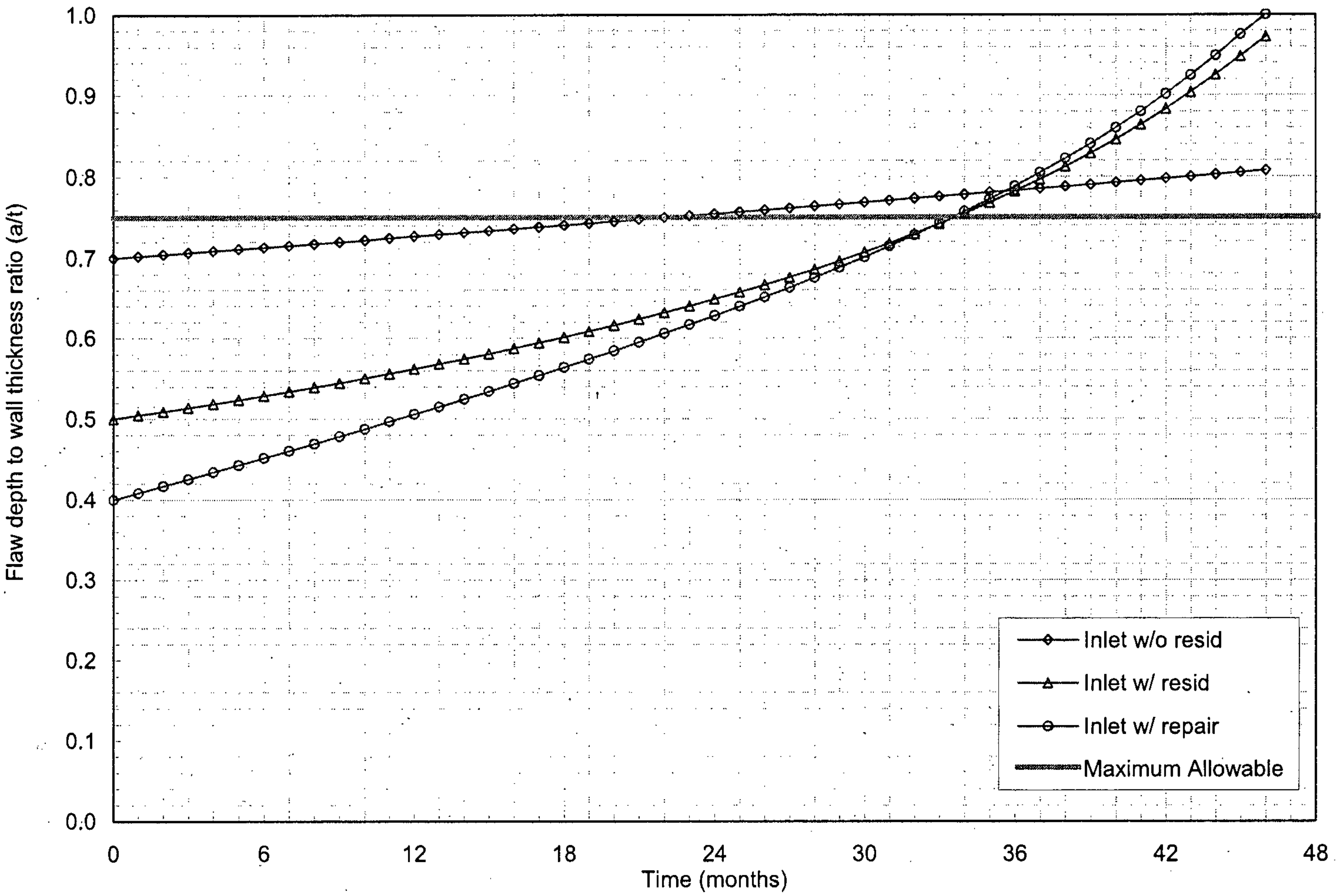

Figure 4-9 Axial Flaw Growth for Pump Suction/Discharge Nozzles

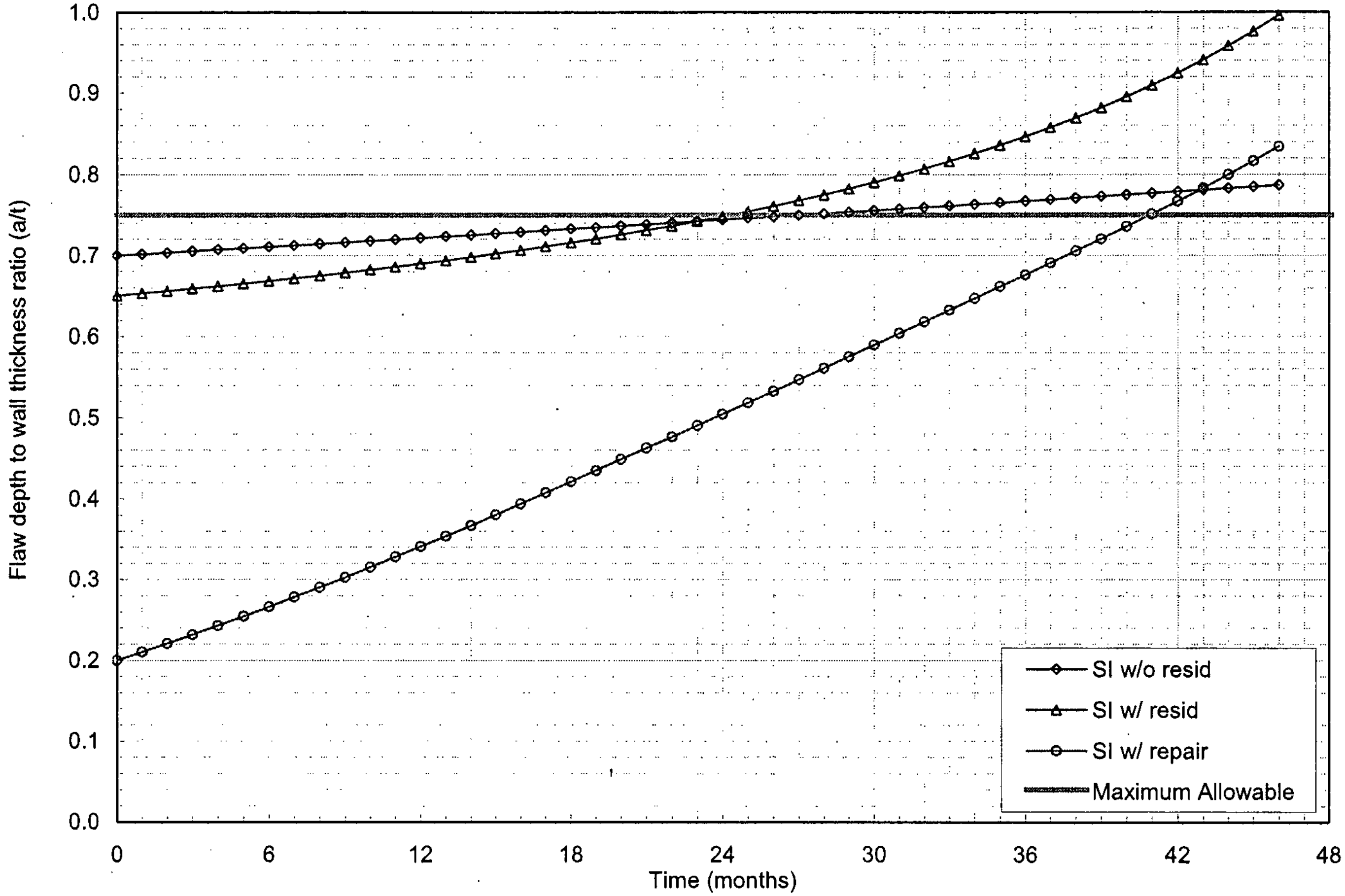

Figure 4-10 Axial Flaw Growth for SI Nozzles

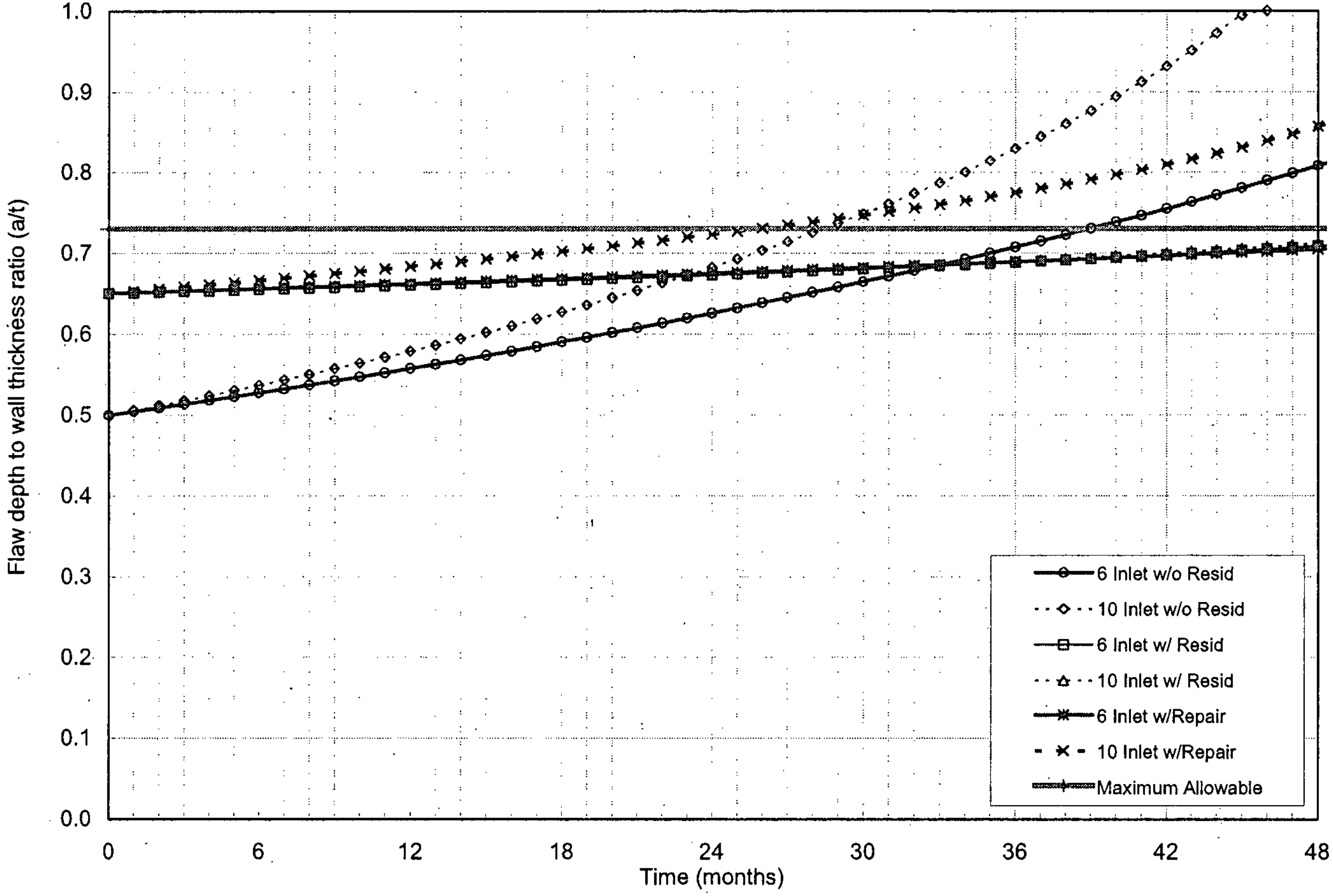

Figure 4-11 Circumferential Flaw Growth for Pump Suction/Discharge Nozzles

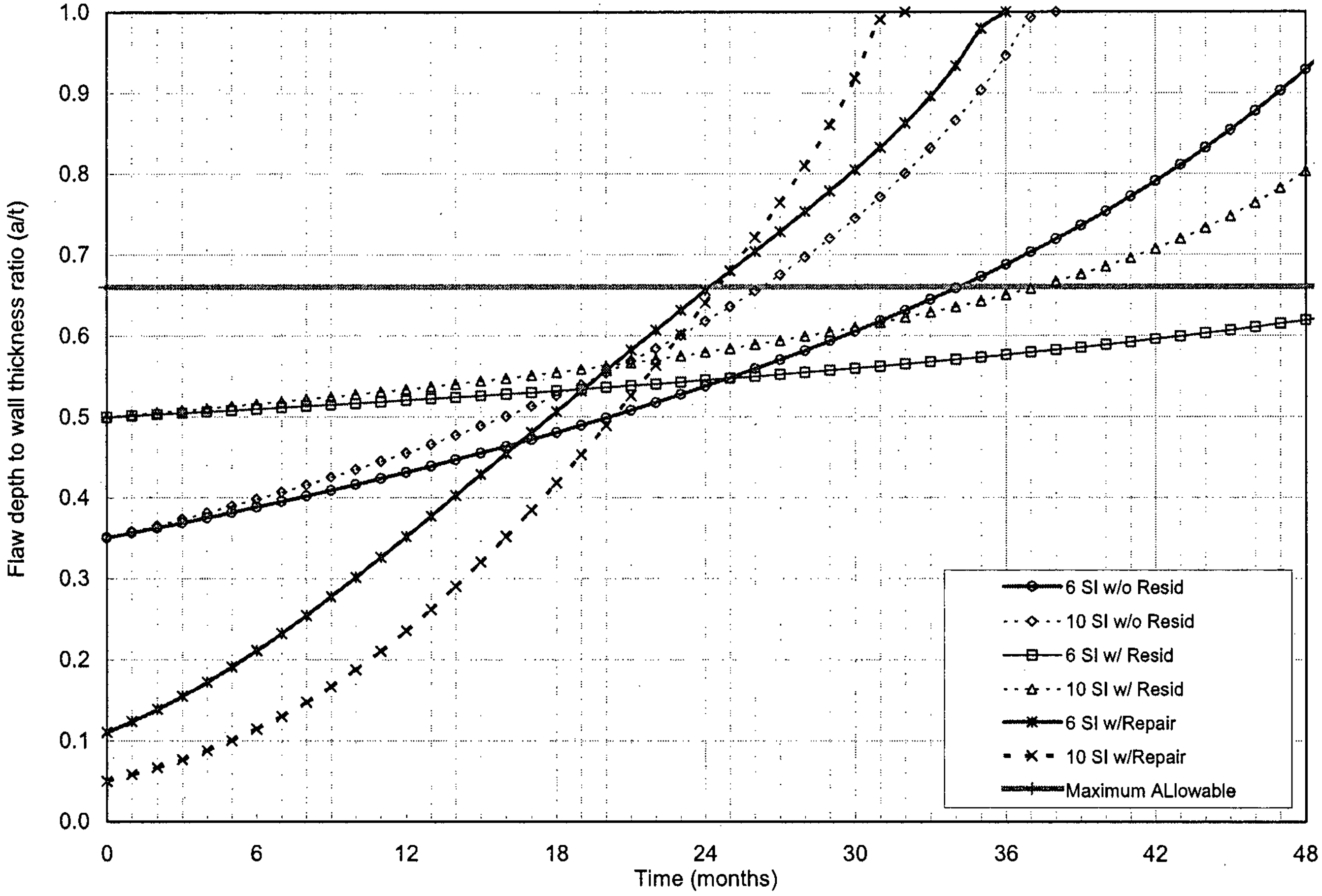

Figure 4-12 Circumferential Flaw Growth for SI Nozzles

5 REFERENCES

1. "Rules for In-Service Inspection of Nuclear Power Plant Component," ASME Code Section XI, 2001 Edition.

2. EPRI Report MRP-139, "Reliability Program: Primary System Piping Butt Weld Inspection and Evaluation Guideline," Palo Alto, CA: 2005, July 4, 2005.

3. EPRI Report MRP-113, "Materials Reliability Program: Alloy 82/182 Pipe Butt Weld Safety Assessment for US PWR Plant Designs," Final Report, April 2005.

4. EPRI Report MRP-216, Rev. 1, "Advanced FEA Simulation of Growth of Postulated Circumferential PWSCC Flaws in Pressurizer Nozzle Dissimilar Metal Welds," Palo Alto, CA, August 2007.

5. EPRI Report MRP-115, "Materials Reliability Program Crack Growth Rates for Evaluating Primary Water Stress Corrosion Cracking (PWSCC) of Alloy 82, 182, and 132 Welds," Final Report, Palo Alto, CA: 2005, November 2004.

6. Bamford, W., R. Cipolla, D. Rudland, and G. DeBoo, "Technical Basis for Revisions to Section XI Appendix C for Alloy 600/82/182/132 Flaw Evaluation in Both PWR and BWR Environments," Proceedings of 2008 ASME Pressure Vessels and Piping Division Conference, July 28-31, 2008, Chicago, USA.

7. Westinghouse Letter LTR-MRCDA-08-104, Rev. 0, "Transmittal of Nozzle Design Loads for Use in PWROG Fracture Mechanics Analyses," May 5, 2008.

8. Westinghouse Calculation Note CN-PAFM-07-155, Rev. 0, "Feasibility Assessment for Continual Operation with Detected Flaws in the Alloy 82/182 Butt Welds of St. Lucie Units 1 and 2 RCP Inlet/Outlet Nozzles and Safety Injection Nozzles," December 5, 2007.

9. Westinghouse Calculation Note CN-RCDA-04-46, Rev. 1, "Weld Overlay - Material Properties," Table 6-8, June 19, 2006.

10. Westinghouse Calculation Note CN-PAFM-05-55, Rev. 0, "Verification and Validation for KCAL_PWSCC Version 3.0," October 2005.

11. Westinghouse Calculation Note CN-PAFM-05-58, Rev. 0, "User's Manual for KCAL_PWSCC Version 3.0," October 2005.

12. Mettu, S. R., I. S. Raju, and R. G. Forman, Report No. NASA-TM-111707, "Stress Intensity Factors for Part-through Surface Cracks in Hollow Cylinders," NASA Lyndon B. Johnson Space Center, Structures and Mechanics Division, July 1992.

13. Chapuliot, S., M. H. Lacire, and P. Le Delliou, "Stress Intensity Factors For Internal Circumferential Cracks In Tubes Over A Wide Range Of Radius Over Thickness Ratios," American Society of Mechanical Engineers (ASME) Pressure Vessels and Piping Conference Proceedings PVP-Vol. 365, 1998, p 95-106.

14. Westinghouse Calculation Note CN-MRCDA-08-37, Rev. 0, "Reactor Coolant Pump and Safety Injection Nozzle Design Information for Fracture Mechanics Evaluation of CE-Designed DM Welds," June 16, 2008.

15. Westinghouse Design Specification 18767-31-5, Rev. 17, "Engineering Specification for a Reactor Coolant Pipe & Fittings for Northeast Utilities Service Company Millstone Point Station, Unit No. 2," March 28, 2008.

16. Westinghouse Engineering Specification 19367-31-5, Rev. 14, "Engineering Specification for Reactor Coolant Pipe & Fittings for Florida Power and Light Company St. Lucie Plant Unit No. 1," June 8, 1993.

17. Westinghouse Engineering Specification 13172-31-5, Rev. 07, "Engineering Specification for Reactor Coolant Pipe & Fittings for Florida Power and Light Company St. Lucie Plant Unit No. 2," June 8, 1993.

18. Westinghouse Design Specification 8067-31-5, Rev. 18, "Engineering Specification for Reactor Coolant Pipe and Fittings for CCNPP 1&2," May 21, 2004.

19. Westinghouse Design Specification 06370-PE-140, Rev. 10, "Project Specification for Reactor Coolant Pipe and Fittings for Arkansas Nuclear One – Unit 2," November 7, 2000.

20. Westinghouse Design Specification 09270-PE-140, Rev. 10, "Project Specification for Reactor Coolant Pipe and Fittings for Entergy Operations, Inc. Waterford Unit No. 3," February 19, 2008.

21. Westinghouse Design Specification 01370-PE-140, Rev. 14, "Project Specification for Reactor Coolant Pipe and Fittings for Southern California Edison San Onofre Unit No. 2," August 24, 2006.

22. Westinghouse Design Specification 01470-PE-140, Rev. 9, "Project Specification for Reactor Coolant Pipe and Fittings for Southern California Edison San Onofre Unit No. 3," August 24, 2006.

23. Westinghouse Design Specification 14273-PE-140, Rev. 15, "Project Specification for Reactor Coolant Pipe and Fittings for Arizona Nuclear Power Project," June 25, 2007.

24. Westinghouse Correspondence FS-99-010, Rev. 001, "Adequacy of the Thermal-Hydraulic Transients in the Current RCS Component Specifications After the Installation of the Replacement Steam Generators (RSGs)," December 12, 2000.