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Title PB-1 CRDM NOZZLE IDTB J-GROOVE WELD FLAW EVALUATION

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PURPOSE AND SUMMARY OF RESULTS:

Revision 1: This revision is a non-proprietary version of Revision 0.

The purpose of the present analysis is to assess the suitability of leaving degraded J-groove weld material in the Point Beach Unit 1 reactor vessel head following the repair of a CRDM nozzle by the ID temper bead weld procedure. It is postulated that a small flaw in the head would combine with a large stress corrosion crack in the weld to form a radial corner flaw that would propagate into the low alloy steel head by fatigue crack growth under cyclic loading conditions.

Based on an evaluation of fatigue crack growth into the low alloy steel head and considering the Section XI requirements of the ASME Code for fracture toughness, a postulated [ ]" radial crack in the Alloy 182 J-groove weld would be acceptable for 25 years of operation.

THE FOLLOWING COMPUTER CODES HAVE BEEN USED IN THIS DOCUMENT:		THE DOCUMENT CONTAINS ASSUMPTIONS THAT MUST BE VERIFIED PRIOR TO USE ON SAFETY-RELATED WORK
CODE/VERSION/REV	CODE/VERSION/REV	☐ YES ☒ NO

RECORD OF REVISIONS

Revision	Affected Pages	Description of Revision	Date
0	All	Original release	9/02
1	All	Revision 1 is a non-proprietary version of Revision 0.	2/03

CONTENTS

1.0 Introduction

Due to the susceptibility of Alloy 600 partial penetration nozzles to primary water stress corrosion cracking (PWSCC), a repair procedure has been developed for reactor vessel head control rod drive mechanism (CRDM) nozzles at Point Beach Unit 1 (PB-1) wherein the lower portion of a degraded nozzle is removed by a boring procedure and the remaining portion of the nozzle is welded to the low alloy steel reactor vessel head above the original Alloy 182 J-groove attachment weld, as shown in Figure 1. This repair design is more fully described by the design drawing [1] and the technical requirements document [2]. Except for a chamfer at the corner, the original J-groove weld will not be removed. Since a potential flaw in the J-groove weld can not be sized by currently available non-destructive examination techniques, it must be assumed that the "as-left" condition of the remaining J-groove weld includes degraded or cracked weld material extending through the entire J-groove weld and Alloy 182 butter material. The purpose of the present analysis is to determine from a fracture mechanics viewpoint the suitability of leaving degraded J-groove weld material in the vessel following the repair of a CRDM nozzle.

From analysis of similar CRDM nozzle penetrations in B&W-designed reactor vessel heads [3], it is known that hoop stresses in the J-groove weld are generally about two times the axial stress at the same location. Since it is expected that this same trend would apply to the PB-1 nozzles, the preferential direction for cracking would be axial, or radial relative to the nozzle. It is postulated that a radial crack in the Alloy 182 weld metal would propagate by PWSCC, through the weld and butter, to the interface with the low alloy steel head. It is fully expected that such a crack would then blunt and arrest at the butter-to-head interface [4]. Since the height of the original weld along the bored surface is about $1^3/_4$", a radial crack depth extending from the corner of the weld to the low alloy steel head would be very deep. Ductile crack growth through the Alloy 182 material would tend to relieve the residual stresses in the weld as the crack grew to its final size and blunted. Although residual stresses in the head material are low (and even compressive) [7], it is assumed that a small flaw could initiate in the low alloy steel material and grow by fatigue. For the present analysis of the remaining J-groove weld, it is postulated that a small flaw in the head would combine with the stress corrosion crack in the weld to form a large radial corner flaw that would propagate into the low alloy steel head by fatigue crack growth under cyclic loading conditions associated with heatup and cooldown.

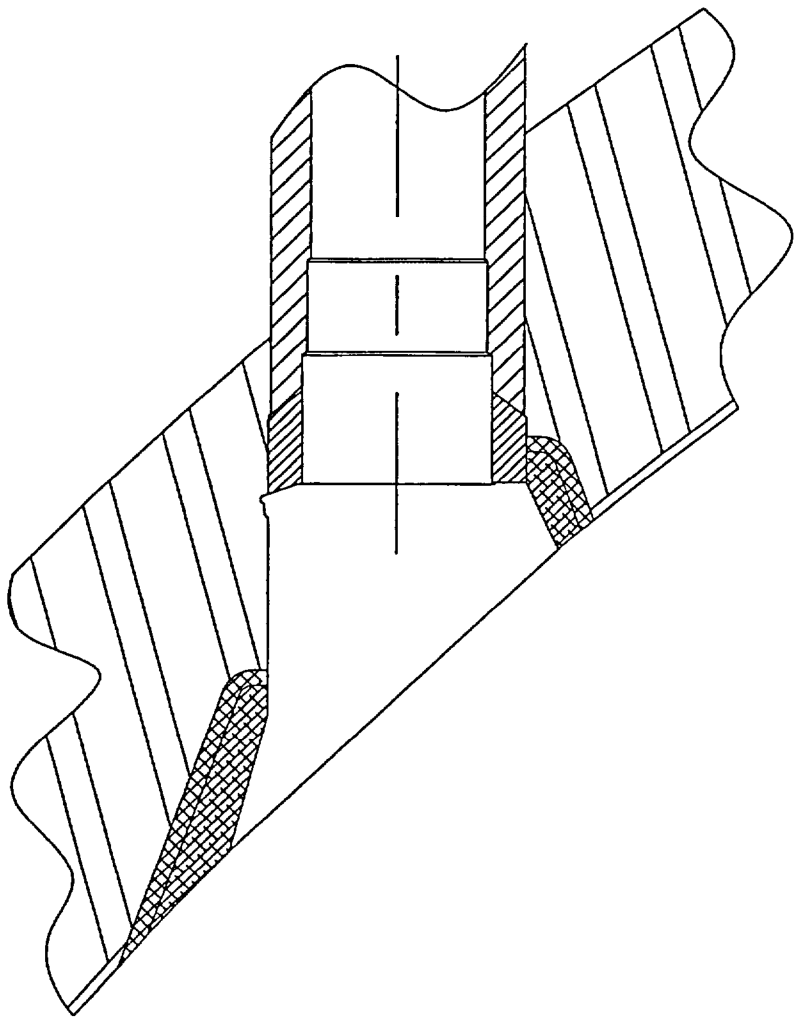

Figure 1. ID Temper Bead Weld Repair

2.0 Geometry and Flaw Model

It is postulated that a radial flaw is present in the low alloy steel head, extending from the chamfered corner of the remaining J-groove weld to the interface between the butter and head. Analytically, this flaw is crudely simulated using the corner flaw model shown below in Figure 2.

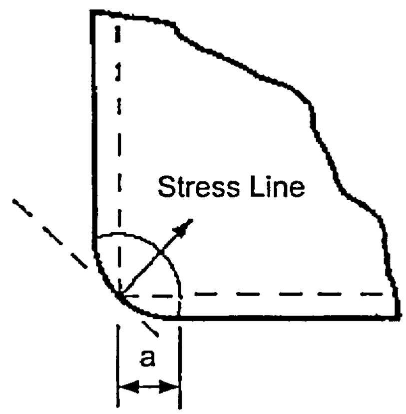

Figure 2. Corner Flaw Model

The flaw depth, "a", is the radius to the crack front. The stress line shown in the figure above depicts a typical direction for consideration of a one-dimensional variation of stress through the area represented by the corner flaw model.

Since a large flaw would have to be postulated if the J-groove weld was left in its original configuration after removal of the nozzle in the ID temper bead repair procedure, the design drawing [1] specifies a chamfer at the inside corner of the remaining weld to limit the height of the weld along the bored surface, from the inside corner to the low alloy steel head, to [ ]". This configuration was modeled in a three-dimensional finite element structural analysis [6] to determine operating stresses throughout the remaining weld, nozzle, and head. The finite element model of the outermost nozzle location includes a detailed geometrical representation of the remaining J-groove weld prep around the penetration. Stresses are reported along a line originating at the inside corner (Point 0) and oriented about 30° relative to the vertical bored surface on the downhill and uphill sides of the nozzle, as shown in Figure 3. The modeled distance along the line, from Point 0 to the interface between the butter and head, is used to represent the depth of the postulated corner flaw. From Reference 6, the initial flaw depth is

a = [ ] in. on the downhill side

and

a = [ ] in. on the uphill side

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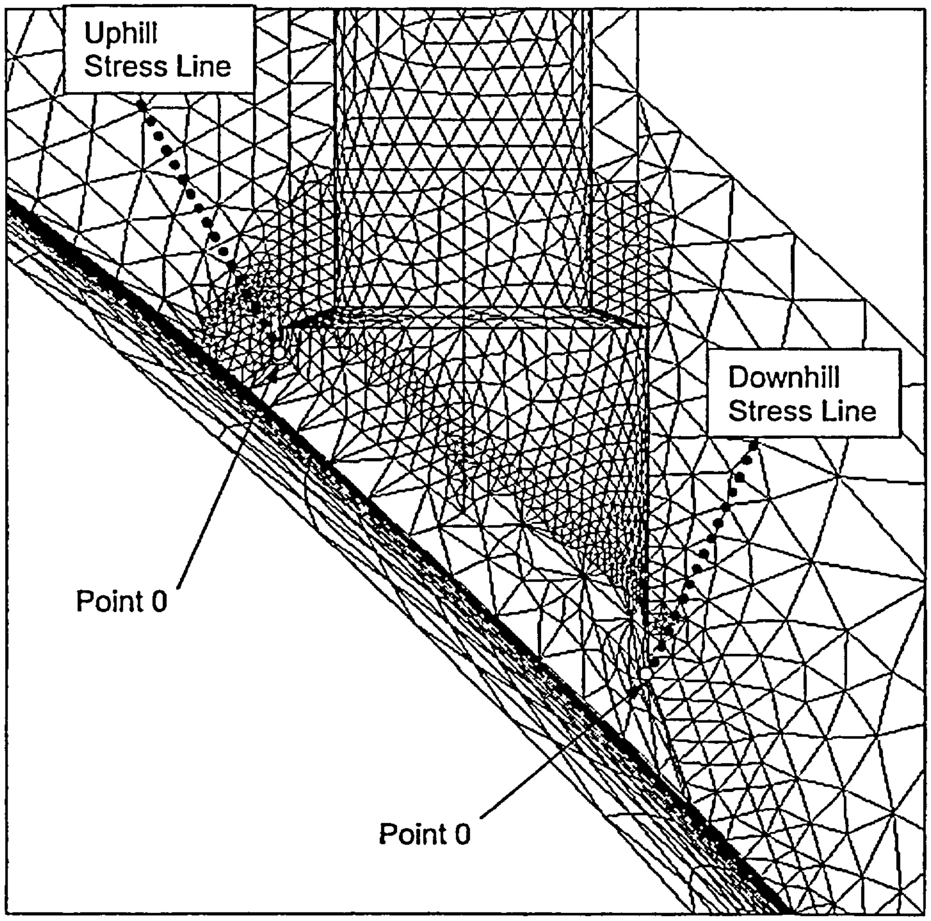


Figure 3. Orientation of Stress Lines

3.0 Material Properties

The portion of the reactor vessel head that contains the CRDM nozzles is fabricated from [ ] [2].

Yield Strength

From the ASME Code, Section III, Appendix I [8], the specified minimum yield strength for the head material is 50.0 ksi below 100 °F and 43.8 ksi at 600 °F. The value at 600 °F is used as a conservative lower bound for yield strengths at operating temperatures less than 600 °F.

Reference Temperature

A reference temperature of 60 °F is used for the RT_{NDT} of the [ ] low alloy reactor vessel head material. This value is commonly used to conservatively represent low alloy ferritic steels.

Fracture Toughness

The lower bound K_{Ia} curve of Section XI, Appendix A, Figure A-4200-1 [9], which can be expressed as

$$K_{Ia} = 26.8 + 12.445 \exp [0.0145 (T - RT_{NDT})] , \qquad \text{[9 (Article A-4200)]}$$

represents the fracture toughness for crack arrest, where T is the crack tip temperature and RT_{NDT} is the reference nil-ductility temperature of the material. K_{Ia} is in ksi$\sqrt{in}$, and T and RT_{NDT} are in °F. In the present flaw evaluations, K_{Ia} is limited to a maximum value of 200 ksi$\sqrt{in}$ (upper-shelf fracture toughness). Using the above equation with an RT_{NDT} of 60 °F, K_{Ia} equals 200 ksi$\sqrt{in}$ at a crack tip temperature of 242 °F.

Fatigue Crack Growth

Flaw growth due to cyclic loading is calculated using the fatigue crack growth rate model from Article A-4300 of Section XI [9],

$$\frac{da}{dN} = C_o(\Delta K_I)^n,$$

where ΔK_I is the stress intensity factor range in ksi$\sqrt{in}$ and da/dN is in inches/cycle. The crack growth rates for a surface flaw will be used for the evaluation of the corner crack since it is assumed that the degraded condition of the J-groove weld and butter exposes the low alloy steel head material to the primary water environment.

Fatigue Crack Growth Rates for Low Alloy Ferritic Steels in a Primary Water Environment

Source: ASME Code, Section XI, 1998 Edition through 2000 Addenda [9] (Corrected)

$$\Delta KI = KI_{max} - KI_{min}$$
$$R = KI_{min} / KI_{max}$$

$0 \le R \le 0.25$: $\Delta K_I < 17.74$,

$n = 5.95$
$C_o = 1.02 \times 10^{-12} \times S$
$S = 1.0$

$\Delta K_I \ge 17.74$,

$n = 1.95$
$C_o = 1.01 \times 10^{-7} \times S$
$S = 1.0$

$0.25 \le R \le 0.65$: $\Delta K_I < 17.74\,[\,(3.75R + 0.06) / (26.9R - 5.725)\,]^{0.25}$,

$n = 5.95$
$C_o = 1.02 \times 10^{-12} \times S$
$S = 26.9R - 5.725$

$\Delta K_I \ge 17.74\,[\,(3.75R + 0.06) / (26.9R - 5.725)\,]^{0.25}$,

$n = 1.95$
$C_o = 1.01 \times 10^{-7} \times S$
$S = 3.75R + 0.06$

$0.65 \le R < 1.0$: $\Delta K_I < 12.04$,

$n = 5.95$
$C_o = 1.02 \times 10^{-12} \times S$
$S = 11.76$

$\Delta K_I \ge 12.04$,

$n = 1.95$
$C_o = 1.01 \times 10^{-7} \times S$
$S = 2.5$

4.0 Fracture Mechanics Methodology

The corner crack is analyzed using the following stress intensity factor solution:

$$K_I = \sqrt{\pi a}\left[0.706(A_0 + A_p) + 0.537\left(\frac{2a}{\pi}\right)A_1 + 0.448\left(\frac{a^2}{2}\right)A_2 + 0.393\left(\frac{4a^3}{3\pi}\right)A_3\right],$$

[Ref. 10, Eqn. (G-2.2)]

where a is the depth of the crack and A_p is a term added to the Reference 10 solution to account for pressure on the crack face.

The stress distribution in the radial direction is described by the third-order polynomial,

$$\sigma = A_0 + A_1 x + A_2 x^2 + A_3 x^3,$$ [Ref. 10, Eqn. (G-2.1)]

where x is measured from the inside corner.

<u>Irwin Plasticity Correction</u>

The Irwin plasticity correction is used to account for a moderate amount of yielding at the crack tip. For plane strain conditions, this correction is defined by

$$r_y = \frac{1}{6\pi}\left(\frac{K_I(a)}{\sigma_y}\right)^2,$$

where,

$K_I(a)$ = stress intensity factor based on the actual crack length, a,
σ_y = material yield strength.

A stress intensity factor, $K_I(a_e)$, is then calculated based on the effective crack length,

$$a_e = a + r_y.$$

5.0 Applied Stresses

Operational stresses are obtained from the results of a three-dimensional linear finite element analysis of the outermost CRDM nozzle head penetration that addresses the configuration after repair by the ID temper bead weld procedure of Reference 1. Stresses are available from Reference 6 at the 0° (downhill) and 180° (uphill) sides of the nozzle bore for seven transients: plant heatup and cooldown, plant loading and unloading, 10% step load increase and decrease, 50% step load reduction, reactor trip, loss of flow, and loss of load. Stresses were reported in a cylindrical coordinate system relative to the nozzle so that the stress directions remain constant around the nozzle. For the most part, the largest hoop stresses at the crack tip are at the downhill side of the nozzle bore (0° location). These stresses are perpendicular to the crack face and tend to open the corner crack. The operational stresses from Reference 6, calculated for the outermost CRDM nozzle location, conservatively bound the stresses at all other nozzle locations.

Table 1 presents the maximum and minimum hoop stresses for each transient. Due to the dominating influence of pressure on stress, stresses remain positive for all transient conditions. Stresses are listed in Table 1 for the downhill (0°) location as a function of the radial position along the stress line shown in Figures 2 and 3. Nine positions are used to report stresses along the stress line: the first 4 positions are within the weld material, the fifth position is at the butter/head interface, and the last 4 positions are located in the reactor vessel head base metal.

Table 1. Operational Hoop Stresses on Downhill Side [6]

Parameter	Loading Condition							
Transient	Heatup/Cooldown		Plant Loading/Unloading		10% Load Changes		50% Load Reduction	
Time	0.001 hr.	6.0 hr.	0.333 hr.	3.333 hr.	0.0625 hr.	1.025 hr.	0.05 hr.	0.233 hr.
Temperature	100 °F	540 °F	612 °F	547 °F	587 °F	602 °F	590 °F	548 °F
Pressure	[ ] psig	[ ] psig	[ ] psig	[ ] psig	[ ] psig	[ ] psig	[ ] psig	[ ] psig
x (in.)*	SY (psi)	SY (psi)	SY (psi)	SY (psi)	SY (psi)	SY (psi)	SY (psi)	SY (psi)
0.0000	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
0.2022	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
0.4043	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
0.6065	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
0.8087	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
1.1043	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
1.3999	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
1.6955	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
1.9911	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]

* Cumulative distance along path line PW_0 in Reference 6.

Table 1. Operational Hoop Stresses on Downhill Side [6] (Cont'd)

Parameter	Loading Condition					
Transient	Reactor Trip		Loss of Flow		Loss of Load	
Time	0.0167 hr.	0.025 hr.	0.001 hr.	0.0403 hr.	0.00278 hr.	0.0444 hr.
Temperature	550 °F	547 °F	612 °F	528 °F	655 °F	550 °F
Pressure	[ ] psig	[ ] psig	[ ] psig	[ ] psig	[ ] psig	[ ] psig
x (in.)*	SY (psi)	SY (psi)	SY (psi)	SY (psi)	SY (psi)	SY (psi)
0.0000	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
0.2022	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
0.4043	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
0.6065	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
0.8087	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
1.1043	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
1.3999	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
1.6955	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
1.9911	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]

* Cumulative distance along path line PW_0 in Reference 6.

Residual stresses are not considered in the present flaw evaluations since a crack that has propagated all the way through the weld and butter would tend to relieve these stresses. A three-dimensional elastic-plastic finite element analysis was performed by Dominion Engineering, Inc. [7] to simulate the sequence of steps involved in arriving at the configuration of the CRDM nozzle and RV head after completion of the ID temper bead repair. This analysis simulated the heatup of the weld, butter, and adjacent material during the welding process and the subsequent cooldown to ambient temperature, a pre-service hydro test, and operation at steady state conditions. After the steady state loads were removed, and the structure was again at ambient conditions, the lower portion of the nozzle was deleted from the model, the new ID temper bead repair weld was added using an 8-pass weld simulation, and the J-groove weld was chamfered by removing selected elements. The stresses associated with this repair configuration are the residual stresses corresponding to an unflawed structure.

The residual stresses from the Dominion Engineering analysis are listed in Table 2 and plotted in Figure 5. These stresses are in the original weld, after chamfering. Although the residual hoop stress in the weld region is high, up to about [ ] psi, the stress decreases to zero within the butter region and is compressive in the head. These stresses would be relieved as the crack propagates through the weld, so that only the operating stresses from Table 1 need be considered when evaluating a crack at the butter-to-head interface.

Table 2.
Residual Hoop Stresses in the Unflawed Structure
After Nozzle Removal, 8-Pass Weld Simulation, and Chamfer [7]

ANSYS Load Step: 20011

Node	Global Coordinates X (in.)	Global Coordinates Z (in.)	ΔS[1] (in.)	Location	Hoop Stress (psi)
1309	2.0000	66.802	0.000	Inside Surface of Weld	[
1412	2.1810	66.961	0.241	Weld	
1615	2.3895	67.162	0.530	Weld/Butter Interface	
1818	2.6315	67.425	0.887	Butter/Head Interface	
1918	2.6694	67.648	1.113	Head	
2018	2.7072	67.871	1.339	Head	
2118	2.7451	68.093	1.565	Head	
2218	2.7830	68.316	1.791	Head	
2318	2.8209	68.539	2.017	Head	
2418	2.8587	68.762	2.243	Head	
2518	2.9163	69.100	2.586	Head	
2618	2.9815	69.484	2.976	Head	
2718	3.0556	69.920	3.418	Head	]

[1] Distance along a stress line, originating at the inside corner of the chamfered weld, and passing through the "outside corner" of the J-groove weld prep (see Figure 4).

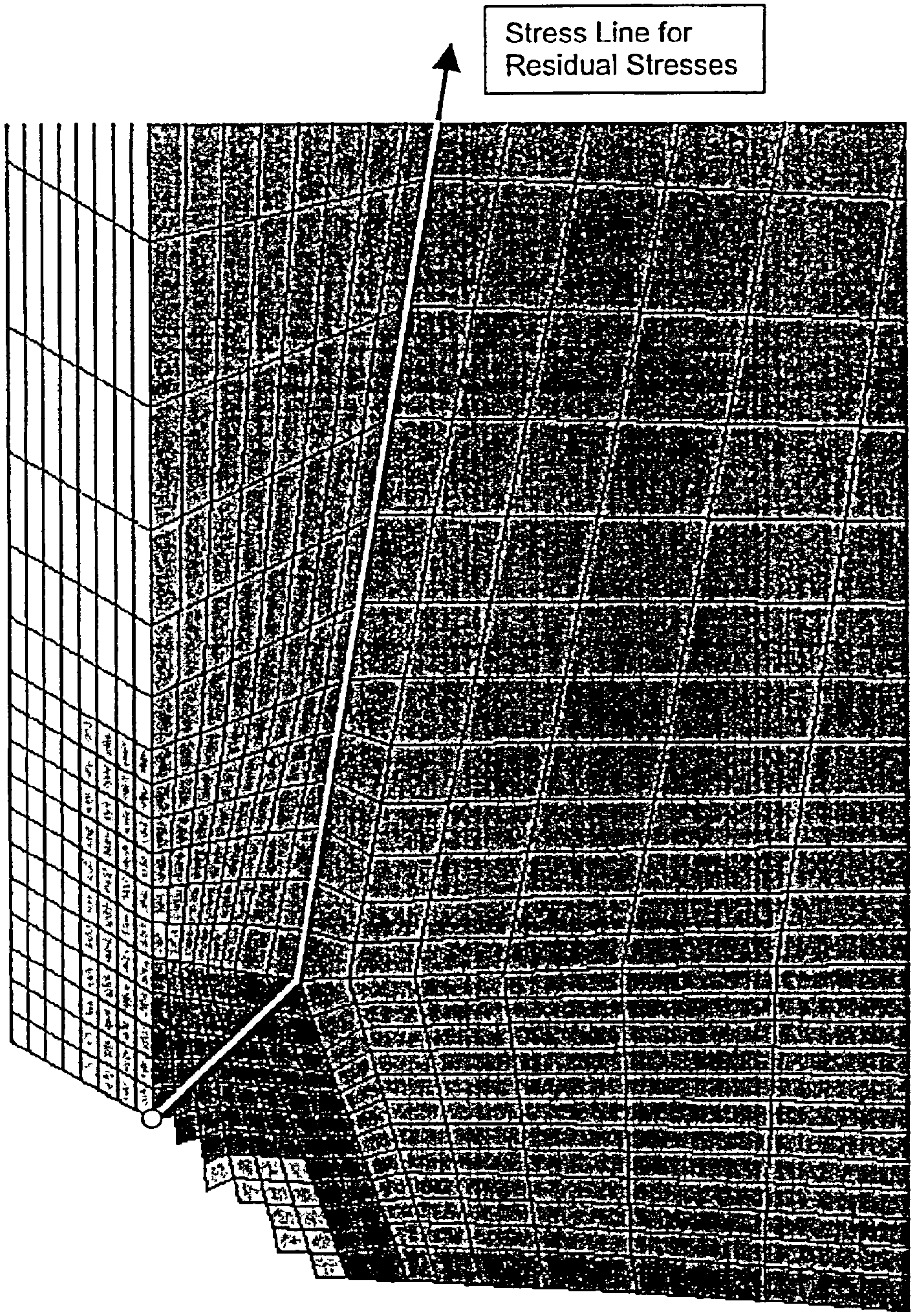
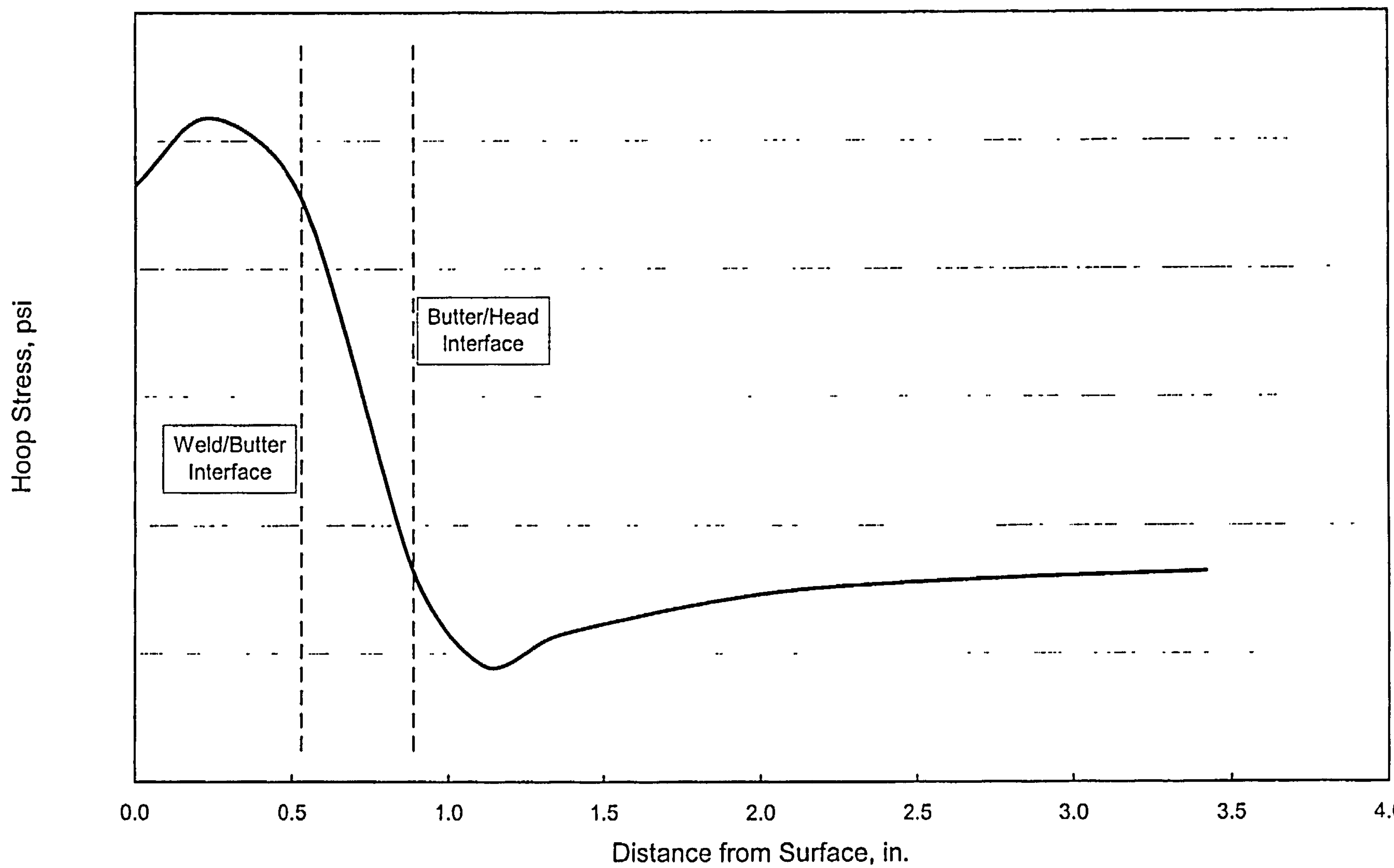


Figure 4. Weld Geometry After Chamfer

Figure 5. Residual Hoop Stresses After Weld Repair



6.0 Flaw Evaluations

A fracture mechanics analysis is performed considering fatigue crack growth over 25 years of service to determine a final flaw size for calculating stress intensity factors for comparison with the fracture toughness requirements of Section XI. Article IWB-3612 [10] requires that a safety factor of $\sqrt{10}$ be used when comparing the applied stress intensity factor to the material fracture toughness. Calculations are performed for a postulated radial corner crack on the downhill side of the outermost CRDM nozzle head penetration.

The actual fracture mechanics calculations are presented in Tables 3 through 9 for the seven transients considered in the finite element stress analysis [6]. Operational hoop stresses perpendicular to the plane of the postulated crack are obtained from Table 1. Fatigue crack growth is calculated on a yearly basis using the following pattern for accumulating cycles:

Table	Transient	Cycles / 40 Years	Cycles / Year
3	Heatup and Cooldown	200	5
4	Plant Loading and Unloading	3,000	75
5	10% Step Load Changes	2,000	50
6	50% Step Load Reduction	200	5
7	Reactor Trip	400	10
8	Loss of Flow	80	2
9	Loss of Load	80	2

These cycles are distributed uniformly over the 25 year service life by linking the incremental crack growth between Tables 3 through 9.

Table 3. Evaluation of CRDM Nozzle Corner Crack for Heatup/Cooldown

INPUT DATA

Initial Flaw Size: Depth, a = [ ] in.

Material Data: Yield strength, S_y = 43.8 ksi

Reference temp., RTndt = 60 F
Upper shelf tough. = 200 ksi√in

KIa = 26.8 + 12.445 exp [0.0145 (T - RTndt)]

KIa is limited to the upper shelf toughness.

Applied Loads:

	Loading Conditions	
	SS*	HU**
	Temperature (F)	
	540	100
	Pressure (ksi)	
	KIa (ksi√in)	
Position	200	49
x	Hoop Stress	
(in.)	(ksi)	(ksi)
0.0000		
0.2022		
0.4043		
0.6065		
0.8087		
1.1043		
1.3999		
1.6955		
1.9911		

* Heatup/Cooldown Transient at 6.0 hours (steady state)
** Heatup/Cooldown Transient at 0.001 hours (low temperature)

Table 3. Evaluation of CRDM Nozzle Corner Crack for Heatup/Cooldown (Cont'd)

STRESS INTENSITY FACTOR

$$KI(a) = \sqrt{(\pi a)}\ [\ 0.706(A_0+A_p) + 0.537(2a/\pi)A_1 + 0.448(a^2/2)A_2 + 0.393(4a^3/3\pi)A_3\ ]$$

where the through-wall stress distribution is described by the third order polynomial,

$$S(x) = A_0 + A_1x + A_2x^2 + A_3x^3,$$

defined by:

Stress Coeff.	Loading Conditions	
	SS	HU
	(ksi)	(ksi)
A_0		
A_1		
A_2		
A_3		

Effective crack size:

$$a_e = a + 1/(6\pi)^*[KI(a)/S_y]^2$$

Effective stress intensity factor:

$$KI(a_e) = \sqrt{(\pi a_e)}\ [\ 0.706(A_0+A_p) + 0.537(2a_e/\pi)A_1 + 0.448(a_e^{\,2}/2)A_2 + 0.393(4a_e^{\,3}/3\pi)A_3\ ]$$

Table 3. Evaluation of CRDM Nozzle Corner Crack for Heatup/Cooldown (Cont'd)

FATIGUE CRACK GROWTH

Transient Description: 200 cycles over 40 years

ΔN = 5 cycles/year

Operating Time (yr.)	Cycle	a (in.)	SS KI(a) (ksi√in)	HU KI(a) (ksi√in)	ΔKI (ksi√in)	Δa (in.)	SS a_e (in.)	HU a_e (in.)	SS $KI(a_e)$ (ksi√in)	HU $KI(a_e)$ (ksi√in)	SS Margin = KIa / $KI(a_e)$	HU Margin = KIa / $KI(a_e)$
0	0		41.63	7.34	34.28	0.00050			42.58	7.35	4.70	6.67
1	5		41.77	7.37	34.40	0.00050			42.72	7.37	4.68	6.65
2	10		41.91	7.39	34.52	0.00050			42.86	7.40	4.67	6.63
3	15		42.05	7.42	34.64	0.00051			43.00	7.42	4.65	6.60
4	20		42.20	7.44	34.75	0.00051			43.14	7.45	4.64	6.58
5	25		42.34	7.47	34.87	0.00051			43.27	7.47	4.62	6.56
6	30		42.48	7.49	34.98	0.00052			43.41	7.50	4.61	6.54
7	35		42.61	7.52	35.10	0.00052			43.55	7.52	4.59	6.52
8	40		42.75	7.54	35.21	0.00052			43.68	7.55	4.58	6.50
9	45		42.89	7.56	35.33	0.00053			43.82	7.57	4.56	6.48
10	50		43.03	7.59	35.44	0.00053			43.95	7.59	4.55	6.46
11	55		43.16	7.61	35.55	0.00053			44.09	7.62	4.54	6.44
12	60		43.30	7.64	35.66	0.00054			44.22	7.64	4.52	6.42
13	65		43.43	7.66	35.77	0.00054			44.35	7.67	4.51	6.40
14	70		43.57	7.68	35.88	0.00054			44.49	7.69	4.50	6.38
15	75		43.70	7.71	35.99	0.00055			44.62	7.71	4.48	6.36
16	80		43.83	7.73	36.10	0.00055			44.75	7.74	4.47	6.34
17	85		43.97	7.75	36.21	0.00055			44.88	7.76	4.46	6.32
18	90		44.10	7.78	36.32	0.00056			45.00	7.78	4.44	6.30
19	95		44.23	7.80	36.43	0.00056			45.13	7.81	4.43	6.28
20	100		44.36	7.82	36.54	0.00056			45.26	7.83	4.42	6.26
21	105		44.49	7.85	36.64	0.00057			45.38	7.85	4.41	6.24
22	110		44.62	7.87	36.75	0.00057			45.51	7.87	4.39	6.23
23	115		44.74	7.89	36.85	0.00057			45.63	7.90	4.38	6.21
24	120		44.87	7.91	36.96	0.00058			45.76	7.92	4.37	6.19
25	125		45.00	7.94	37.06	0.00058			45.88	7.94	4.36	6.17

Table 3. Evaluation of CRDM Nozzle Corner Crack for Heatup/Cooldown (Cont'd)

FRACTURE TOUGHNESS MARGINS

Period of Operation: Time = 25.00 years

Final Flaw Size: a = [ ] in. (after loss of load transient)

Margin = KIa / KI(a_e)

	Loading Conditions		
	SS	HU	
Fracture Toughness, KIa	200	49	ksi√in
KI(a)	45.12	7.96	ksi√in
a_e			
KI(a_e)	46.00	7.96	ksi√in
Actual Margin	4.35	6.16	
Required Margin	3.16	3.16	

Table 4. Evaluation of CRDM Nozzle Corner Crack for Plant Loading/Unloading

INPUT DATA

Initial Flaw Size: Depth, a = [ ] in.

Material Data: Yield strength, S_y = 43.8 ksi

Reference temp., RTndt = 60 F
Upper shelf tough. = 200 ksi√in

KIa = 26.8 + 12.445 exp [0.0145 (T - RTndt)]

KIa is limited to the upper shelf toughness.

Applied Loads:

	Loading Conditions	
	PU*	PL**
	Temperature (F)	
	547	612
	Pressure, p (ksi)	
	KIa (ksi√in)	
Position	200	200
x	Hoop Stress	
(in.)	(ksi)	(ksi)
0.0000		
0.2022		
0.4043		
0.6065		
0.8087		
1.1043		
1.3999		
1.6955		
1.9911		

* Plant Loading/Unloading Transient at 3.333 hours (plant unloading)
** Plant Loading/Unloading Transient at 0.333 hours (plant loading)

Table 4. Evaluation of CRDM Nozzle Corner Crack for Plant Loading/Unloading (Cont'd)

STRESS INTENSITY FACTOR

$$KI(a) = \sqrt{(\pi a)}\ [\ 0.706(A_0+A_p) + 0.537(2a/\pi)A_1 + 0.448(a^2/2)A_2 + 0.393(4a^3/3\pi)A_3\ ]$$

where the through-wall stress distribution is described by the third order polynomial,

$$S(x) = A_0 + A_1x + A_2x^2 + A_3x^3,$$

defined by:

Stress Coeff.	Loading Conditions	
	PU	PL
	(ksi)	(ksi)
A_0		
A_1		
A_2		
A_3		

Effective crack size:

$$a_e = a + 1/(6\pi)^*[KI(a)/S_y]^2$$

Effective stress intensity factor:

$$KI(a_e) = \sqrt{(\pi a_e)}\ [\ 0.706(A_0+A_p) + 0.537(2a_e/\pi)A_1 + 0.448(a_e^2/2)A_2 + 0.393(4a_e^3/3\pi)A_3\ ]$$

Table 4. Evaluation of CRDM Nozzle Corner Crack for Plant Loading/Unloading (Cont'd)

FATIGUE CRACK GROWTH

Transient Description: 3000 cycles over 40 years

ΔN = 75 cycles/year

Operating Time (yr.)	Cycle	a (in.)	PU KI(a) (ksi√in)	PL KI(a) (ksi√in)	ΔKI (ksi√in)	Δa (in.)	PU a_e (in.)	PL a_e (in.)	PU KI(a_e) (ksi√in)	PL KI(a_e) (ksi√in)	PU Margin = KIa / KI(a_e)	PL Margin = KIa / KI(a_e)
0	0		49.86	28.92	20.94	0.00638			51.25	29.30	3.90	6.83
1	75		50.01	29.03	20.97	0.00640			51.39	29.41	3.89	6.80
2	150		50.15	29.15	21.00	0.00643			51.53	29.53	3.88	6.77
3	225		50.30	29.27	21.04	0.00645			51.67	29.65	3.87	6.75
4	300		50.45	29.38	21.07	0.00648			51.81	29.76	3.86	6.72
5	375		50.59	29.50	21.10	0.00650			51.94	29.88	3.85	6.69
6	450		50.74	29.61	21.13	0.00653			52.08	29.99	3.84	6.67
7	525		50.88	29.73	21.16	0.00655			52.21	30.11	3.83	6.64
8	600		51.02	29.84	21.18	0.00657			52.35	30.22	3.82	6.62
9	675		51.16	29.95	21.21	0.00660			52.48	30.33	3.81	6.59
10	750		51.30	30.07	21.24	0.00662			52.61	30.45	3.80	6.57
11	825		51.44	30.18	21.26	0.00664			52.74	30.56	3.79	6.54
12	900		51.58	30.29	21.29	0.00667			52.87	30.67	3.78	6.52
13	975		51.72	30.40	21.31	0.00669			53.00	30.78	3.77	6.50
14	1050		51.85	30.51	21.34	0.00671			53.12	30.89	3.76	6.47
15	1125		51.99	30.63	21.36	0.00673			53.25	31.01	3.76	6.45
16	1200		52.12	30.74	21.38	0.00675			53.37	31.12	3.75	6.43
17	1275		52.25	30.85	21.41	0.00677			53.49	31.23	3.74	6.40
18	1350		52.38	30.96	21.43	0.00679			53.61	31.34	3.73	6.38
19	1425		52.51	31.06	21.45	0.00681			53.73	31.44	3.72	6.36
20	1500		52.64	31.17	21.47	0.00683			53.85	31.55	3.71	6.34
21	1575		52.77	31.28	21.49	0.00685			53.97	31.66	3.71	6.32
22	1650		52.89	31.39	21.50	0.00687			54.09	31.77	3.70	6.30
23	1725		53.02	31.50	21.52	0.00688			54.20	31.87	3.69	6.27
24	1800		53.14	31.60	21.54	0.00690			54.31	31.98	3.68	6.25
25	1875		53.26	31.71	21.55	0.00692			54.43	32.09	3.67	6.23

Table 4. Evaluation of CRDM Nozzle Corner Crack for Plant Loading/Unloading (Cont'd)

FRACTURE TOUGHNESS MARGINS

Period of Operation: Time = 25.00 years

Final Flaw Size: a = [ ] in. (after loss of load transient)

Margin = KIa / KI(a_e)

	Loading Conditions		
	PU	PL	
Fracture Toughness, KIa	200.0	200.0	ksi√in
KI(a)	53.37	31.81	ksi√in
a_e			
KI(a_e)	54.53	32.18	ksi√in
Actual Margin	3.67	6.21	
Required Margin	3.16	3.16	

Table 5. Evaluation of CRDM Nozzle Corner Crack for 10% Step Load Changes

INPUT DATA

Initial Flaw Size:	Depth,	a =	[ ]	in.
Material Data:	Yield strength,	S_y =	43.8	ksi
	Reference temp.,	RTndt =	60	F
	Upper shelf tough.	=	200	ksi√in

Kla = 26.8 + 12.445 exp [0.0145 (T - RTndt)]

Kla is limited to the upper shelf toughness.

Applied Loads:

	Loading Conditions	
	10SI*	10SD**
	Temperature (F)	
	587	602
	Pressure, p (ksi)	
Position	Kla (ksi√in)	
	200	200
x	Hoop Stress	
(in.)	(ksi)	(ksi)
0.0000		
0.2022		
0.4043		
0.6065		
0.8087		
1.1043		
1.3999		
1.6955		
1.9911		

* 10% Step Load Change at 0.0625 hours (step increase)
** 10% Step Load Change at 1.025 hours (step decrease)

Table 5. Evaluation of CRDM Nozzle Corner Crack for 10% Step Load Changes (Cont'd)

STRESS INTENSITY FACTOR

$$KI(a) = \sqrt{(\pi a)}\ [\ 0.706(A_0+A_p) + 0.537(2a/\pi)A_1 + 0.448(a^2/2)A_2 + 0.393(4a^3/3\pi)A_3\ ]$$

where the through-wall stress distribution is described by the third order polynomial,

$$S(x) = A_0 + A_1x + A_2x^2 + A_3x^3,$$

defined by:

Stress Coeff.	Loading Conditions	
	10SI	10SD
	(ksi)	(ksi)
A_0		
A_1		
A_2		
A_3		

Effective crack size:

$$a_e = a + 1/(6\pi)^*[KI(a)/S_y]^2$$

Effective stress intensity factor:

$$KI(a_e) = \sqrt{(\pi a_e)}\ [\ 0.706(A_0+A_p) + 0.537(2a_e/\pi)A_1 + 0.448(a_e^2/2)A_2 + 0.393(4a_e^3/3\pi)A_3\ ]$$

Table 5. Evaluation of CRDM Nozzle Corner Crack for 10% Step Load Changes (Cont'd)

FATIGUE CRACK GROWTH

Transient Description: 2000 cycles over 40 years

ΔN = 50 cycles/year

Operating Time (yr.)	Cycle	a (in.)	10SI KI(a) (ksi√in)	10SD KI(a) (ksi√in)	ΔKI (ksi√in)	Δa (in.)	10SI a_e (in.)	10SD a_e (in.)	10SI KI(a_e) (ksi√in)	10SD KI(a_e) (ksi√in)	10SI Margin = KIa / KI(a_e)	10SD Margin = KIa / KI(a_e)
0	0		41.82	38.45	3.37	0.00000			42.73	39.20	4.68	5.10
1	50		41.96	38.58	3.38	0.00000			42.87	39.34	4.67	5.08
2	100		42.09	38.71	3.38	0.00000			43.00	39.47	4.65	5.07
3	150		42.23	38.85	3.38	0.00000			43.13	39.60	4.64	5.05
4	200		42.36	38.98	3.39	0.00000			43.27	39.73	4.62	5.03
5	250		42.50	39.11	3.39	0.00000			43.40	39.86	4.61	5.02
6	300		42.63	39.24	3.39	0.00000			43.53	39.98	4.59	5.00
7	350		42.77	39.37	3.40	0.00000			43.66	40.11	4.58	4.99
8	400		42.90	39.50	3.40	0.00000			43.78	40.24	4.57	4.97
9	450		43.03	39.63	3.40	0.00000			43.91	40.36	4.55	4.95
10	500		43.16	39.75	3.40	0.00000			44.04	40.49	4.54	4.94
11	550		43.29	39.88	3.41	0.00000			44.16	40.61	4.53	4.92
12	600		43.42	40.01	3.41	0.00000			44.29	40.74	4.52	4.91
13	650		43.54	40.13	3.41	0.00000			44.41	40.86	4.50	4.89
14	700		43.67	40.26	3.41	0.00000			44.53	40.98	4.49	4.88
15	750		43.80	40.38	3.42	0.00000			44.65	41.10	4.48	4.87
16	800		43.92	40.50	3.42	0.00000			44.77	41.22	4.47	4.85
17	850		44.05	40.62	3.42	0.00000			44.89	41.34	4.45	4.84
18	900		44.17	40.75	3.42	0.00000			45.01	41.46	4.44	4.82
19	950		44.29	40.87	3.42	0.00000			45.13	41.58	4.43	4.81
20	1000		44.41	40.99	3.43	0.00000			45.25	41.69	4.42	4.80
21	1050		44.53	41.10	3.43	0.00000			45.36	41.81	4.41	4.78
22	1100		44.65	41.22	3.43	0.00000			45.48	41.92	4.40	4.77
23	1150		44.77	41.34	3.43	0.00000			45.59	42.04	4.39	4.76
24	1200		44.89	41.46	3.43	0.00000			45.70	42.15	4.38	4.75
25	1250		45.00	41.57	3.43	0.00000			45.81	42.26	4.37	4.73

Table 5. Evaluation of CRDM Nozzle Corner Crack for 10% Step Load Changes (Cont'd)

FRACTURE TOUGHNESS MARGINS

Period of Operation: Time = 25.00 years

Final Flaw Size: a = [ ] in. (after loss of load transient)

Margin = $K_{Ia} / K_I(a_e)$

	Loading Conditions		
	10SI	10SD	
Fracture Toughness, KIa	200.0	200.0	ksi√in
KI(a)	45.01	41.57	ksi√in
a_e			
KI(a_e)	45.82	42.26	ksi√in
Actual Margin	4.37	4.73	
Required Margin	3.16	3.16	

Table 6. Evaluation of CRDM Nozzle Corner Crack for 50% Step Load Reduction

INPUT DATA

Initial Flaw Size:	Depth,	a =	[ ]	in.
Material Data:	Yield strength,	S_y =	43.8	ksi
	Reference temp.,	RTndt =	60	F
	Upper shelf tough.	=	200	ksi√in

$$KIa = 26.8 + 12.445 \exp [0.0145 (T - RTndt)]$$

KIa is limited to the upper shelf toughness.

Applied Loads:

	Loading Conditions	
	50SR1*	50SR2**
	Temperature (F)	
	548	590
	Pressure, p (ksi)	
	KIa (ksi√in)	
Position	200	200
x	Hoop Stress	
(in.)	(ksi)	(ksi)
0.0000		
0.2022		
0.4043		
0.6065		
0.8087		
1.1043		
1.3999		
1.6955		
1.9911		

* 50% Step Load Reduction at 0.233 hours (max. stress)
** 50% Step Load Reduction at 0.05 hours (min. stress)

Table 6. Evaluation of CRDM Nozzle Corner Crack for 50% Step Load Reduction (Cont'd)

STRESS INTENSITY FACTOR

$$KI(a) = \sqrt{(\pi a)}\ [\ 0.706(A_0+A_p) + 0.537(2a/\pi)A_1 + 0.448(a^2/2)A_2 + 0.393(4a^3/3\pi)A_3\ ]$$

where the through-wall stress distribution is described by the third order polynomial,

$$S(x) = A_0 + A_1x + A_2x^2 + A_3x^3,$$

defined by:

Stress Coeff.	Loading Conditions	
	50SR1	50SR2
	(ksi)	(ksi)
A_0		
A_1		
A_2		
A_3		

Effective crack size:

$$a_e = a + 1/(6\pi)*[KI(a)/S_y]^2$$

Effective stress intensity factor:

$$KI(a_e) = \sqrt{(\pi a_e)}\ [\ 0.706(A_0+A_p) + 0.537(2a_e/\pi)A_1 + 0.448(a_e^2/2)A_2 + 0.393(4a_e^3/3\pi)A_3\ ]$$

Table 6. Evaluation of CRDM Nozzle Corner Crack for 50% Step Load Reduction (Cont'd)

FATIGUE CRACK GROWTH

Transient Description: 200 cycles over 40 years

ΔN = 5 cycles/year

Operating Time (yr.)	Cycle	a (in.)	50SR1 KI(a) (ksi√in)	50SR2 KI(a) (ksi√in)	ΔKI (ksi√in)	Δa (in.)	50SR1 a_e (in.)	50SR2 a_e (in.)	50SR1 $KI(a_e)$ (ksi√in)	50SR2 $KI(a_e)$ (ksi√in)	50SR1 Margin = KIa / $KI(a_e)$	50SR2 Margin = KIa / $KI(a_e)$
0	0		43.12	38.95	4.17	0.00000			44.07	39.74	4.54	5.03
1	5		43.25	39.09	4.17	0.00000			44.20	39.88	4.52	5.02
2	10		43.39	39.22	4.17	0.00000			44.33	40.01	4.51	5.00
3	15		43.52	39.36	4.16	0.00000			44.46	40.14	4.50	4.98
4	20		43.66	39.49	4.16	0.00000			44.59	40.28	4.49	4.97
5	25		43.79	39.63	4.16	0.00000			44.72	40.41	4.47	4.95
6	30		43.92	39.76	4.16	0.00000			44.85	40.54	4.46	4.93
7	35		44.05	39.89	4.16	0.00000			44.97	40.67	4.45	4.92
8	40		44.18	40.02	4.16	0.00000			45.10	40.80	4.43	4.90
9	45		44.31	40.15	4.15	0.00000			45.22	40.92	4.42	4.89
10	50		44.43	40.28	4.15	0.00000			45.34	41.05	4.41	4.87
11	55		44.56	40.41	4.15	0.00000			45.47	41.18	4.40	4.86
12	60		44.69	40.54	4.15	0.00000			45.59	41.30	4.39	4.84
13	65		44.81	40.67	4.14	0.00000			45.71	41.43	4.38	4.83
14	70		44.94	40.80	4.14	0.00000			45.83	41.55	4.36	4.81
15	75		45.06	40.92	4.14	0.00000			45.95	41.68	4.35	4.80
16	80		45.18	41.05	4.14	0.00000			46.06	41.80	4.34	4.78
17	85		45.30	41.17	4.13	0.00000			46.18	41.92	4.33	4.77
18	90		45.42	41.30	4.13	0.00000			46.30	42.04	4.32	4.76
19	95		45.54	41.42	4.13	0.00000			46.41	42.16	4.31	4.74
20	100		45.66	41.54	4.12	0.00000			46.52	42.28	4.30	4.73
21	105		45.78	41.66	4.12	0.00000			46.64	42.40	4.29	4.72
22	110		45.90	41.78	4.11	0.00000			46.75	42.52	4.28	4.70
23	115		46.01	41.90	4.11	0.00000			46.86	42.64	4.27	4.69
24	120		46.13	42.02	4.11	0.00000			46.97	42.75	4.26	4.68
25	125		46.24	42.14	4.10	0.00000			47.08	42.87	4.25	4.67

Table 6. Evaluation of CRDM Nozzle Corner Crack for 50% Step Load Reduction (Cont'd)

FRACTURE TOUGHNESS MARGINS

Period of Operation: Time = 25.00 years

Final Flaw Size: a = [ ] in. (after loss of load transient)

Margin = KIa / $KI(a_e)$

	Loading Conditions		
	50SR1	50SR2	
Fracture Toughness, KIa	200.0	200.0	ksi√in
KI(a)	46.24	42.14	ksi√in
a_e			
$KI(a_e)$	47.08	42.87	ksi√in
Actual Margin	4.25	4.67	
Required Margin	3.16	3.16	

Table 7. Evaluation of CRDM Nozzle Corner Crack for Reactor Trip

INPUT DATA

Initial Flaw Size:	Depth,	a =	[ ]	in.
Material Data:	Yield strength,	S_y =	43.8	ksi
	Reference temp.,	RTndt =	60	F
	Upper shelf tough.	=	200	ksi√in

Kla = 26.8 + 12.445 exp [0.0145 (T - RTndt)]

Kla is limited to the upper shelf toughness.

Applied Loads:

	Loading Conditions	
	RT1*	RT2**
	Temperature (F)	
	547	550
	Pressure, p (ksi)	
Position	Kla (ksi√in)	
	200	200
x	Hoop Stress	
(in.)	(ksi)	(ksi)
0.0000		
0.2022		
0.4043		
0.6065		
0.8087		
1.1043		
1.3999		
1.6955		
1.9911		

* Reactor Trip Transient at 0.025 hours (max. stress)
** Reactor Trip Transient at 0.0167 hours (min. stress)

Table 7. Evaluation of CRDM Nozzle Corner Crack for Reactor Trip (Cont'd)

STRESS INTENSITY FACTOR

$$KI(a) = \sqrt{(\pi a)}\,[\,0.706(A_0+A_p) + 0.537(2a/\pi)A_1 + 0.448(a^2/2)A_2 + 0.393(4a^3/3\pi)A_3\,]$$

where the through-wall stress distribution is described by the third order polynomial,

$$S(x) = A_0 + A_1x + A_2x^2 + A_3x^3,$$

defined by:

Stress Coeff.	Loading Conditions	
	RT1	RT2
	(ksi)	(ksi)
A_0		
A_1		
A_2		
A_3		

Effective crack size:

$$a_e = a + 1/(6\pi)^*[KI(a)/S_y]^2$$

Effective stress intensity factor:

$$KI(a_e) = \sqrt{(\pi a_e)}\,[\,0.706(A_0+A_p) + 0.537(2a_e/\pi)A_1 + 0.448(a_e^2/2)A_2 + 0.393(4a_e^3/3\pi)A_3\,]$$

Table 7. Evaluation of CRDM Nozzle Corner Crack for Reactor Trip (Cont'd)

FATIGUE CRACK GROWTH

Transient Description: 400 cycles over 40 years

ΔN = 10 cycles/year

Operating Time (yr.)	Cycle	a (in.)	RT1 KI(a) (ksi√in)	RT2 KI(a) (ksi√in)	ΔKI (ksi√in)	Δa (in.)	RT1 a_e (in.)	RT2 a_e (in.)	RT1 $KI(a_e)$ (ksi√in)	RT2 $KI(a_e)$ (ksi√in)	RT1 Margin = KIa / $KI(a_e)$	RT2
0	0		46.23	43.60	2.63	0.00000			47.21	44.42	4.24	4.50
1	10		46.36	43.71	2.64	0.00000			47.32	44.53	4.23	4.49
2	20		46.48	43.83	2.65	0.00000			47.44	44.64	4.22	4.48
3	30		46.60	43.94	2.65	0.00000			47.55	44.75	4.21	4.47
4	40		46.72	44.06	2.66	0.00000			47.66	44.85	4.20	4.46
5	50		46.84	44.17	2.67	0.00000			47.77	44.96	4.19	4.45
6	60		46.95	44.28	2.67	0.00000			47.88	45.06	4.18	4.44
7	70		47.07	44.39	2.68	0.00000			47.99	45.17	4.17	4.43
8	80		47.18	44.50	2.69	0.00000			48.09	45.27	4.16	4.42
9	90		47.30	44.60	2.69	0.00000			48.20	45.37	4.15	4.41
10	100		47.41	44.71	2.70	0.00000			48.30	45.47	4.14	4.40
11	110		47.52	44.82	2.70	0.00000			48.40	45.57	4.13	4.39
12	120		47.63	44.92	2.71	0.00000			48.50	45.66	4.12	4.38
13	130		47.74	45.02	2.72	0.00000			48.60	45.76	4.11	4.37
14	140		47.85	45.13	2.72	0.00000			48.70	45.85	4.11	4.36
15	150		47.95	45.23	2.73	0.00000			48.80	45.95	4.10	4.35
16	160		48.06	45.33	2.73	0.00000			48.90	46.04	4.09	4.34
17	170		48.16	45.43	2.74	0.00000			48.99	46.13	4.08	4.34
18	180		48.27	45.52	2.74	0.00000			49.08	46.22	4.07	4.33
19	190		48.37	45.62	2.75	0.00000			49.18	46.31	4.07	4.32
20	200		48.47	45.72	2.75	0.00000			49.27	46.40	4.06	4.31
21	210		48.57	45.81	2.76	0.00000			49.36	46.49	4.05	4.30
22	220		48.67	45.90	2.76	0.00000			49.45	46.57	4.04	4.29
23	230		48.76	46.00	2.77	0.00000			49.54	46.66	4.04	4.29
24	240		48.86	46.09	2.77	0.00000			49.62	46.74	4.03	4.28
25	250		48.95	46.18	2.77	0.00000			49.71	46.82	4.02	4.27

Table 7. Evaluation of CRDM Nozzle Corner Crack for Reactor Trip (Cont'd)

FRACTURE TOUGHNESS MARGINS

Period of Operation: Time = 25.00 years

Final Flaw Size: a = [ ] in. (after loss of load transient)

Margin = $K_{Ia} / K_I(a_e)$

	Loading Conditions		
	RT1	RT2	
Fracture Toughness, KIa	200.0	200.0	ksi√in
KI(a)	48.95	46.18	ksi√in
a_e			
$K_I(a_e)$	49.71	46.83	ksi√in
Actual Margin	4.02	4.27	
Required Margin	3.16	3.16	

Table 8. Evaluation of CRDM Nozzle Corner Crack for Loss of Flow

INPUT DATA

Initial Flaw Size: Depth, a = [ ] in.

Material Data: Yield strength, S_y = 43.8 ksi

Reference temp., RTndt = 60 F

Upper shelf tough. = 200 ksi√in

KIa = 26.8 + 12.445 exp [0.0145 (T - RTndt)]

KIa is limited to the upper shelf toughness.

Applied Loads:

	Loading Conditions	
	LF1*	LF2**
	Temperature (F)	
	528	612
	Pressure, p (ksi)	
	KIa (ksi√in)	
Position	200	200
x	Hoop Stress	
(in.)	(ksi)	(ksi)
0.0000		
0.2022		
0.4043		
0.6065		
0.8087		
1.1043		
1.3999		
1.6955		
1.9911		

* Loss of Flow Transient at 0.0403 hours (max. stress)

** Loss of Flow Transient at 0.001 hours (min. stress)

Table 8. Evaluation of CRDM Nozzle Corner Crack for Loss of Flow (Cont'd)

STRESS INTENSITY FACTOR

$$KI(a) = \sqrt{(\pi a)}\,[\,0.706(A_0+A_p) + 0.537(2a/\pi)A_1 + 0.448(a^2/2)A_2 + 0.393(4a^3/3\pi)A_3\,]$$

where the through-wall stress distribution is described by the third order polynomial,

$$S(x) = A_0 + A_1x + A_2x^2 + A_3x^3,$$

defined by:

Stress Coeff.	Loading Conditions	
	LF1	LF2
	(ksi)	(ksi)
A_0		
A_1		
A_2		
A_3		

Effective crack size:

$$a_e = a + 1/(6\pi)*[KI(a)/S_y]^2$$

Effective stress intensity factor:

$$KI(a_e) = \sqrt{(\pi a_e)}\,[\,0.706(A_0+A_p) + 0.537(2a_e/\pi)A_1 + 0.448(a_e^2/2)A_2 + 0.393(4a_e^3/3\pi)A_3\,]$$

Table 8. Evaluation of CRDM Nozzle Corner Crack for Loss of Flow (Cont'd)

FATIGUE CRACK GROWTH

Transient Description: 80 cycles over 40 years

ΔN = 2 cycles/year

Operating Time (yr.)	Cycle	a (in.)	LF1 KI(a) (ksi√in)	LF2 KI(a) (ksi√in)	ΔKI (ksi√in)	Δa (in.)	LF1 a_e (in.)	LF2 a_e (in.)	LF1 $KI(a_e)$ (ksi√in)	LF2 $KI(a_e)$ (ksi√in)	LF1 Margin = KIa / $KI(a_e)$	LF2
0	0		57.41	40.69	16.72	0.00012			59.22	41.54	3.38	4.81
1	2		57.56	40.83	16.73	0.00012			59.36	41.67	3.37	4.80
2	4		57.71	40.96	16.75	0.00012			59.49	41.81	3.36	4.78
3	6		57.86	41.10	16.77	0.00012			59.63	41.94	3.35	4.77
4	8		58.01	41.23	16.78	0.00012			59.76	42.06	3.35	4.75
5	10		58.16	41.36	16.80	0.00012			59.89	42.19	3.34	4.74
6	12		58.30	41.49	16.81	0.00012			60.02	42.32	3.33	4.73
7	14		58.44	41.62	16.82	0.00012			60.14	42.45	3.33	4.71
8	16		58.59	41.75	16.84	0.00012			60.27	42.57	3.32	4.70
9	18		58.73	41.88	16.85	0.00012			60.39	42.70	3.31	4.68
10	20		58.87	42.01	16.86	0.00012			60.51	42.82	3.31	4.67
11	22		59.00	42.13	16.87	0.00012			60.64	42.94	3.30	4.66
12	24		59.14	42.26	16.88	0.00012			60.75	43.07	3.29	4.64
13	26		59.28	42.38	16.89	0.00013			60.87	43.19	3.29	4.63
14	28		59.41	42.51	16.90	0.00013			60.99	43.31	3.28	4.62
15	30		59.54	42.63	16.91	0.00013			61.10	43.43	3.27	4.61
16	32		59.67	42.75	16.92	0.00013			61.22	43.55	3.27	4.59
17	34		59.80	42.87	16.93	0.00013			61.33	43.66	3.26	4.58
18	36		59.93	43.00	16.93	0.00013			61.44	43.78	3.26	4.57
19	38		60.05	43.12	16.94	0.00013			61.55	43.90	3.25	4.56
20	40		60.18	43.23	16.94	0.00013			61.65	44.01	3.24	4.54
21	42		60.30	43.35	16.95	0.00013			61.76	44.12	3.24	4.53
22	44		60.42	43.47	16.95	0.00013			61.86	44.24	3.23	4.52
23	46		60.54	43.59	16.96	0.00013			61.96	44.35	3.23	4.51
24	48		60.66	43.70	16.96	0.00013			62.06	44.46	3.22	4.50
25	50		60.78	43.81	16.96	0.00013			62.16	44.57	3.22	4.49

Table 8. Evaluation of CRDM Nozzle Corner Crack for Loss of Flow (Cont'd)

FRACTURE TOUGHNESS MARGINS

Period of Operation: Time = 25.00 years

Final Flaw Size: a = [ ] in. (after loss of load transient)

Margin = KIa / KI(a_e)

	Loading Conditions		
	LF1	LF2	
Fracture Toughness, KIa	200.0	200.0	ksi√in
KI(a)	60.78	43.82	ksi√in
a_e			
KI(a_e)	62.16	44.57	ksi√in
Actual Margin	3.22	4.49	
Required Margin	3.16	3.16	

Table 9. Evaluation of CRDM Nozzle Corner Crack for Loss of Load

INPUT DATA

Initial Flaw Size:	Depth,	a =	[ ]	in.
Material Data:	Yield strength,	S_y =	43.8	ksi
	Reference temp.,	RTndt =	60	F
	Upper shelf tough.	=	200	ksi√in

KIa = 26.8 + 12.445 exp [0.0145 (T - RTndt)]

KIa is limited to the upper shelf toughness.

Applied Loads:

	Loading Conditions	
	LL1*	LL2**
	Temperature (F)	
	655	550
	Pressure, p (ksi)	
Position	KIa (ksi√in)	
	200	200
x	Hoop Stress	
(in.)	(ksi)	(ksi)
0.0000		
0.2022		
0.4043		
0.6065		
0.8087		
1.1043		
1.3999		
1.6955		
1.9911		

* Loss of Load Transient at 0.00278 hours (max. stress)
** Loss of Load Transient at 0.0444 hours (min. stress)

Table 9. Evaluation of CRDM Nozzle Corner Crack for Loss of Load (Cont'd)

STRESS INTENSITY FACTOR

$$KI(a) = \sqrt{(\pi a)}\,[\,0.706(A_0+A_p) + 0.537(2a/\pi)A_1 + 0.448(a^2/2)A_2 + 0.393(4a^3/3\pi)A_3\,]$$

where the through-wall stress distribution is described by the third order polynomial,

$$S(x) = A_0 + A_1x + A_2x^2 + A_3x^3,$$

defined by:

Stress Coeff.	Loading Conditions	
	LL1	LL2
	(ksi)	(ksi)
A_0		
A_1		
A_2		
A_3		

Effective crack size:

$$a_e = a + 1/(6\pi)*[KI(a)/S_y]^2$$

Effective stress intensity factor:

$$KI(a_e) = \sqrt{(\pi a_e)}\,[\,0.706(A_0+A_p) + 0.537(2a_e/\pi)A_1 + 0.448(a_e^2/2)A_2 + 0.393(4a_e^3/3\pi)A_3\,]$$

Table 9. Evaluation of CRDM Nozzle Corner Crack for Loss of Load (Cont'd)

FATIGUE CRACK GROWTH

Transient Description: 80 cycles over 40 years

ΔN = 2 cycles/year

Operating Time (yr.)	Cycle	a (in.)	LL1 KI(a) (ksi√in)	LL2 KI(a) (ksi√in)	ΔKI (ksi√in)	Δa (in.)	LL1 a_e (in.)	LL2 a_e (in.)	LL1 $KI(a_e)$ (ksi√in)	LL2 $KI(a_e)$ (ksi√in)	LL1 Margin = KIa / $KI(a_e)$	LL2 Margin = KIa / $KI(a_e)$
0	0		47.76	36.78	10.98	0.00004			49.23	37.27	4.06	5.37
1	2		47.93	36.88	11.06	0.00004			49.40	37.36	4.05	5.35
2	4		48.10	36.97	11.13	0.00004			49.57	37.45	4.04	5.34
3	6		48.27	37.06	11.21	0.00004			49.73	37.54	4.02	5.33
4	8		48.44	37.16	11.28	0.00004			49.90	37.63	4.01	5.32
5	10		48.61	37.25	11.36	0.00005			50.06	37.71	4.00	5.30
6	12		48.77	37.34	11.44	0.00005			50.22	37.80	3.98	5.29
7	14		48.94	37.43	11.51	0.00005			50.38	37.88	3.97	5.28
8	16		49.10	37.51	11.59	0.00005			50.54	37.97	3.96	5.27
9	18		49.27	37.60	11.67	0.00005			50.70	38.05	3.94	5.26
10	20		49.43	37.69	11.74	0.00006			50.86	38.13	3.93	5.24
11	22		49.59	37.77	11.82	0.00006			51.01	38.21	3.92	5.23
12	24		49.75	37.86	11.89	0.00006			51.17	38.29	3.91	5.22
13	26		49.91	37.94	11.97	0.00006			51.32	38.37	3.90	5.21
14	28		50.07	38.03	12.05	0.00006			51.48	38.45	3.89	5.20
15	30		50.23	38.11	12.12	0.00007			51.63	38.53	3.87	5.19
16	32		50.39	38.19	12.20	0.00007			51.78	38.60	3.86	5.18
17	34		50.54	38.27	12.27	0.00007			51.93	38.68	3.85	5.17
18	36		50.70	38.35	12.35	0.00007			52.08	38.75	3.84	5.16
19	38		50.85	38.43	12.42	0.00007			52.22	38.83	3.83	5.15
20	40		51.00	38.50	12.50	0.00007			52.37	38.90	3.82	5.14
21	42		51.15	38.58	12.58	0.00007			52.52	38.97	3.81	5.13
22	44		51.30	38.65	12.65	0.00007			52.66	39.04	3.80	5.12
23	46		51.45	38.73	12.73	0.00007			52.80	39.11	3.79	5.11
24	48		51.60	38.80	12.80	0.00007			52.94	39.18	3.78	5.11
25	50		51.75	38.87	12.88	0.00007			53.08	39.24	3.77	5.10

Table 9. Evaluation of CRDM Nozzle Corner Crack for Loss of Load (Cont'd)

FRACTURE TOUGHNESS MARGINS

Period of Operation: Time = 25.00 years

Final Flaw Size: a = [ ] in.

Margin = KIa / KI(a_e)

	Loading Conditions		
	LL1	LL2	
Fracture Toughness, KIa	200.0	200.0	ksi√in
KI(a)	51.75	38.87	ksi√in
a_e			
KI(a_e)	53.08	39.24	ksi√in
Actual Margin	3.77	5.10	
Required Margin	3.16	3.16	

7.0 Summary of Results

A fracture mechanics analysis has been performed to evaluate a postulated large radial crack in the remnants of the original J-groove weld (and butter) at the CRDM nozzle reactor vessel head penetration. Results of this analysis are summarized below for the controlling transient.

Loss of Flow

Temperature,	$T = 528\ ^{\circ}F$
Initial flaw size,	a_i = [ ] in.
Final flaw size after 25 years,	a_f = [ ] in.
Flaw growth,	$a_f - a_i = 0.192$ in.
Stress intensity factor at final flaw size,	$K_I = 62.16\ ksi\sqrt{in}$
Fracture toughness,	$K_{Ia} = 200.0\ ksi\sqrt{in}$
Safety margin:	$K_{Ia} / KI = 3.22 > \sqrt{10} = 3.16$

Conclusion

Based on an evaluation of fatigue crack growth into the low alloy steel head, the above results demonstrate that a postulated radial crack in the Alloy 182 J-groove weld would be acceptable for 25 years of operation, considering the following transient frequencies:

Transient	Frequency (cycles/year)
Heatup and Cooldown	5
Plant Loading and Unloading	75
10% Step Load Changes	50
50% Step Load Reduction	5
Reactor Trip	10
Loss of Flow	2
Loss of Load	2

8.0 References

1. Framatome ANP Drawing 02-5019702E-2, "Point Beach Unit 1 CRDM Nozzle ID Temper Bead Weld Repair."

2. Framatome ANP Document 51-5017195-05, "Point Beach 1 & 2 CRDM Nozzle ID Temper Bead Weld Repair Requirements," September 2002.

3. Framatome ANP Document 51-5011603-01, "RV Head Nozzle and Weld Safety Assessment," April 2001.

4. Framatome ANP Document 51-5012047-00, "Stress Corrosion Cracking of Low Alloy Steel," March 2001.

5. (not used)

6. Framatome ANP Document 32-5020244-01, "Point Beach 1 CRDM Temperbead Bore Weld Analysis," February 2003.

7. Framatome ANP Document 38-1290142-00, "NMC Letter Dated September 24, 2002, Subject: Dominion Engineering Calculations," September 2002.

8. ASME Boiler and Pressure Vessel Code, Section III, Rules for Construction of Nuclear Power Plant Components, Division 1 - Appendices, 1989 Edition with No Addenda.

9. ASME Boiler and Pressure Vessel Code, Section XI, Rules for Inservice Inspection of Nuclear Power Plant Components, 1998 Edition with Addenda through 2000.

10. Marston, T.U., "Flaw Evaluation Procedures – Background and Application of ASME Section XI, Appendix A," EPRI Report NP-719-SR, August 1978.