NMC
Committed to Nuclear Excellence

Point Beach Nuclear Plant
Operated by Nuclear Management Company, LLC

NRC 2003-0067

10 CFR 50.55a(a)(3)(i)
10 CFR 50.55a(g)(5)(iii)

July 31, 2003

U. S. Nuclear Regulatory Commission
ATTN: Document Control Desk
Washington, DC 20555

POINT BEACH NUCLEAR PLANT, UNITS 1 AND 2
DOCKETS 50-266 AND 50-301
REACTOR VESSEL CLOSURE HEAD PENETRATION REPAIR
RELIEF REQUESTS MR 03-018-1 AND MR 02-018-2
SUPPLEMENT 2 AND RESPONSE TO REQUEST FOR ADDITIONAL INFORMATION

Reference: (1) Letter from NMC to NRC dated August 28, 2002 (serial NRC 2002-0073)
(2) Letter from NMC to NRC dated April 10, 2003 (serial NRC 2003-0034)

In Reference 1, Nuclear Management Company, LLC (NMC) submitted Relief Requests MR 02-018-1 and MR 02-018-2 for PBNP Unit 1 (TAC Nos. MB6184 and MB6185). The requested relief may become necessary in the event that flaws requiring repair in reactor vessel closure head (RVCH) penetrations are discovered during upcoming inspections, in accordance with our response to NRC Bulletin 2002-02, "Reactor Pressure Vessel Head and Vessel Head Penetration Nozzle Inspection Programs".

Reference 2 provided additional information in support of the relief request and expanded its applicability to PBNP Unit 2. As such, NMC proposed that the requested relief be approved for both units. Enclosed with reference 2 were copies of supporting calculation packages prepared by Framatome ANP, LLC ("FRA-ANP"). As Calculation Packages 32-5019398-00, 32-5019396-00, and 32-5020244-00 contained information proprietary to FRA-ANP, they were supported by an affidavit signed on September 30, 2002 by FRA-ANP, the owner of the information.

During subsequent conference calls between NMC representatives and NRC staff, the NRC requested additional information in support of the relief requests. The enclosures to this letter contain the NMC response to the staff's questions.

NRC staff also questioned certain aspects of the proprietary classification imposed by FRA-ANP on the information in their calculation packages. The specific calculation packages were:

Calculation Package 32-5019398-01, "PB-1 CRDM Nozzle IDTB Weld Anomaly Flaw Evaluations", dated February 28, 2003 (Non-Proprietary);

Calculation Package 32-5019396-01, "PB-1 CRDM Nozzle IDTB J-Groove Weld Flaw Evaluation", dated February 28, 2003 (Non-Proprietary); and,

Calculation Package 32-5020244-01, "Point Beach 1 CRDM Temperbead Bore Weld Analysis", dated February 28, 2003 (Non-Proprietary)

6590 Nuclear Road • Two Rivers, Wisconsin 54241
Telephone: 920.755.2321

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FRA-ANP subsequently informed NMC that some of the information in the first two of the above three calculation packages was inappropriately classified as proprietary. Therefore, the following revised copies of the non-proprietary versions of the FRA-ANP calculation packages are enclosed with this letter. These two non-proprietary packages replace the corresponding originally submitted packages in their entirety. The technical information in these revised packages is unchanged, only the proprietary classifications were corrected.

Calculation Package 32-5019398-02, "PB-1 CRDM Nozzle IDTB Weld Anomaly Flaw Evaluations", dated July 28, 2003 (Non-Proprietary);

Calculation Package 32-5019396-02, "PB-1 CRDM Nozzle IDTB J-Groove Weld Flaw Evaluation", dated July 28, 2003 (Non-Proprietary)

Also included in the enclosures to this letter is a second FRA-ANP proprietary authorization affidavit, supporting Calculation Packages 32-5019396-02 and 32-5019398-02. The affidavit sets forth the basis on which the information may be withheld from public disclosure by the Commission and addresses with specificity the considerations listed in paragraph (b)(4) of 10 CFR 2.790 of the Commission's regulations.

Accordingly, it is respectfully requested that the information, which is proprietary to FRA-ANP, be withheld from public disclosure in accordance with 10 CFR 2.790. Correspondence regarding the proprietary aspects of the items listed above, or the supporting FRA-ANP Affidavit, should reference the affidavit and be addressed to J. F. Mallay, Director Regulatory Affairs, Framatome ANP, Inc., 3315 Old Forest Road, P.O. Box 10935, Lynchburg, Virginia, 24506-0935.

NMC requests NRC review and approval of these relief requests, for both units, by October 9, 2003. If necessary, NMC personnel will be available to meet with your staff to discuss any concerns you may have.

Any statements of intent made in this submittal are provided for information purposes and are not considered to be regulatory commitments.

A. J. Cayia
A. J. Cayia
Site Vice President

LAS/kmd

Attachment 1: Response to Request for Additional Information

Enclosures

cc: (with enclosures)
Project Manager, Point Beach Nuclear Plant, NRR, USNRC

cc: (w/o enclosures)
Regional Administrator, Region III, USNRC
NRC Resident Inspector - Point Beach Nuclear Plant
PSCW

ATTACHMENT 1

**RESPONSE TO REQUEST FOR ADDITIONAL INFORMATION (RAI)
REGARDING RELIEF REQUEST SUBMITTALS MR 02-018-1 AND MR02-018-2
DATED AUGUST 23, 2002 AND APRIL 10, 2003**

POINT BEACH NUCLEAR PLANT, UNITS 1 AND 2

RESPONSE TO NRC REQUEST FOR ADDITIONAL INFORMATION

The following information is provided in response to the Nuclear Regulatory Commission staff's request for additional information (RAI) on NMC's August 28, 2002 and April 10, 2003 Relief Request submittal, as discussed during several telephone conferences between NRC and NMC staff. The staff's questions were germane to both PBNP units.

The NRC staff's questions are restated below, with the NMC response following. The NMC response is based on the attached calculation packages s provided by Framatome ANP ("FRA-ANP") and applies to both PBNP units.

NRC Question 1:

Please provide the following for Unit 2:

Construction Code Year
Inservice Inspection Year Code of Record with Addenda
Interval Number
Specific Code Sections for which Unit 2 relief is being sought

NMC Response:

Unit 2 Construction Code Year:
ASME Section III - 1968, with Winter 1968 Addenda

Unit 2 Inservice Inspection Year Code of Record with Addenda:
1998 Edition of ASME Section XI with all addenda through 2000

Unit 2 Interval Number:
Fourth inspection interval

Specific Code Sections for which the Unit 2 relief is being sought:
As stated in the August 28, 2002 submittal, NMC requests relief from ASME XI IWA-3300(b), IWB-3142.4 and IWB-3420, which would require characterization of a flaw existing in the remnant of the J-groove weld that will be left on the Point Beach Unit 2 Reactor Vessel Closure Head (RVCH) if a control rod drive mechanism (CRDM) nozzle must be partially removed.

Although references to Unit 1 in the August 28, 2002 submittal may be interchanged with Unit 2, it needs to be noted that the Unit 1 vessel was fabricated IAW 1965 Section III (as stated in the August 28, 2002 submittal), and the Unit 2 vessel was fabricated to 1968 A68 Section III

NRC Question 2:

In your April 10, 2003 letter responding to the staff's RAI, in calculation summary sheet 32-5019398-00, PB-1 CRDM Nozzle IDTB Weld Anomaly Flaw Evaluations, page 4, the statement is made: "This weld repair establishes a new pressure boundary above the original J-groove weld, except in some cases away from the center of the head where the new weld partially overlaps the original weld."

Recent experience at ANO-1 and North Anna, where weld repairs cracked at the junction of the Alloy 52 and Alloy 182 boundary after one cycle of operation have come to light. Taking into considerations the lessons learned from this occurrence, please discuss the actions that will be taken in the area of monitoring the repair for structural and lead integrity when the new repair weld overlaps the remnant J-groove weld.

NMC Response:

The intended service life of this proposed repair is one fuel cycle. The possible overlap that may occur on a repair will not constitute the entire length of the new Alloy 52 weld. Using a conservative confluence of minimum tolerances there will be a satisfactory ligament where the new Alloy 52 weld does not overlap the old Alloy 182 weld and is attached to the low-alloy steel RV head. The actual length of the overlap will be minimized by taking field measurements of RV head thickness and J-groove weld depth instead of using the conservative tolerance values.

The potential for a preexisting flaw to propagate along the boundary between the new Alloy 52 and the low alloy steel (first pass diluted zone) has been considered and is described below.

There have been numerous repairs of Alloy 600 locations in U.S. PWRs using Alloy 52. Many of these repairs resulted in the interface between low alloy steel and an Alloy 52 weld being exposed to primary coolant (examples include 150+ CE PZR nozzle repairs, FRA-ANP's CRDM IDTB process, miscellaneous hot leg and PZR instrument nozzles). Extensive industry operating experience has shown Alloy 52 to be highly resistant to PWSCC, without any such 1st diluted layer cracking as described above. The actual geometry of the overlap in the Point Beach CRDM repair is expected to result in a low crack driving force in the 1st diluted layer due to the small size (~0.070") of such a layer and restraint by surrounding materials. Also, the Alloy 52 weld is applied with an ambient temperature temperbead GTAW process, which minimizes the residual tensile stresses contributing to the crack driving force.

In addition to the evidence described above, the proposed repair weld will have its structural leak integrity verified by volumetric NDE, thereby giving assurance of no pressure boundary leakage.

ENCLOSURES

to

NRC 2003-0067

Calculation Package 32-5019398-02, "PB-1 CRDM Nozzle IDTB Weld Anomaly Flaw Evaluations", dated July 28, 2003 (Non-Proprietary);

Calculation Package 32-5019396-02, "PB-1 CRDM Nozzle IDTB J-Groove Weld Flaw Evaluation", dated July 28, 2003 (Non-Proprietary);

Framatome ANP proprietary authorization AFFIDAVIT

FRAMATOME ANP

CALCULATION SUMMARY SHEET (CSS)

Document Identifier 32 - 5019398 - 02

Title PB-1 CRDM NOZZLE IDTB WELD ANOMALY FLAW EVALUATIONS

PREPARED BY:				REVIEWED BY:			
				METHOD: ☒ DETAILED CHECK ☐ INDEPENDENT CALCULATION			
NAME	D.E. KILLIAN			NAME	H.P. GUNAWARDANE		
SIGNATURE				SIGNATURE			
TITLE	ADVISORY ENGR.	DATE	7/27/03	TITLE	ENGINEER II	DATE	7/28/03
COST CENTER	41629	REF. PAGE(S)	49,50	TM STATEMENT: REVIEWER INDEPENDENCE	gFS for ADM		

PURPOSE AND SUMMARY OF RESULTS:

Revision 2: This revision is a non-proprietary version of Revision 0.

The purpose of this analysis is to perform a fracture mechanics evaluation of a postulated weld anomaly in the Point Beach Unit 1 CRDM nozzle ID temper bead weld repair. The postulated anomaly is a 0.100 inch semi-circular flaw extending 360 degrees around the circumference at the "triple point" location where there is a confluence of three materials; the Alloy 600 nozzle, the Alloy 52/152 weld, and the low alloy steel head. The anomaly is assumed to propagate in each of two directions on the uphill and downhill sides of the nozzle. The analysis predicts fatigue crack growth in an air environment since the anomaly is located on the outside surface of the new weld, just below the bottom of the severed CRDM tube. Flaw acceptance is based on the 1998 with 2000 Addenda ASME Code Section XI criteria for applied stress intensity factor (IWB-3612) and limit load (IWB-3642).

The results of the analysis demonstrate that a 0.100 inch weld anomaly is acceptable for a 25 year design life for the CRDM nozzle ID temper bead weld repair. Significant fracture toughness margins have been demonstrated for each of the two flaw propagation paths considered in the analysis. The minimum fracture toughness margin is 9.57, compared to the required margin of $\sqrt{10}$ per IWB-3612. Fatigue crack growth is minimal. The maximum final flaw size is [ ] inch. The margin on limit load is 8.47, compared to the required margin of 3.0 per IWB-3642.

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	Date
0	All	Original release	9/02
1	All	Revision 1 is a non-proprietary version of Revision 0.	2/03
2	All	Revision 2 is a non-proprietary version of Revision 0 that includes more information than Revision 1.	7/03

TABLE OF CONTENTS

1.0 INTRODUCTION

The CRDM nozzle ID temper bead weld repair is described by the design drawing (Reference 1). This weld repair establishes a new pressure boundary above the original J-groove weld, except in some cases away from the center of the head where the new weld partially overlaps the original weld. There are seven steps involved in the repair design, as depicted in Reference 1. These steps are:

1) Thermal sleeve cutting
2) Roll expansion
3) Nozzle removal and weld prep machining
4) Welding
5) Grinding/machining and NDE
6) Original weld grinding
7) Thermal sleeve re-attachment

During the welding process (step 4), a maximum 0.1 inch weld anomaly may be formed due to lack of fusion at the "triple point", as shown in Figure 1. The anomaly is conservatively assumed to be a "crack-like" defect, 360 degrees around the circumference at the "triple point" location. The technical requirements document (Reference 2) provides additional details of the ID temper bead weld repair procedure. The purpose of the present fracture mechanics analysis is to provide justification, in accordance with Section XI of the ASME Code (Reference 3), for operating with the postulated weld anomaly at the triple point. Predictions of fatigue crack growth are based on a design life of 25 years.

2.0 ASSUMPTIONS

Listed below are assumptions that are pertinent to the present fracture mechanics evaluation.

1) The anomaly is assumed to include a "crack-like" defect, located at the triple-point location and extending all the way around the circumference. For analytical purposes, a continuous circumferential flaw is located in the horizontal plane at the top of the weld. Another continuous flaw is located in the cylindrical plane between the weld and reactor vessel (RV) head.

2) In the radial plane, the anomaly is assumed to include a quarter-circular "crack-like" defect (see Figure 1). For analytical purposes, a semi-circular flaw is used to represent the radial cross-section of the anomaly.

3) It is assumed that the weld residual stresses due to the new repair weld are negligible and therefore can be neglected in the present analysis, as discussed in Reference 5.

4) An RT_{NDT} value of 60 °F is conservatively assumed for the SA-302 Grade B low alloy reactor vessel head material. This value is commonly used to conservatively represent low alloy ferritic steels.

3.0 WELD ANOMALY

The anomaly is located in the triple point region as shown in Figure 1 below.

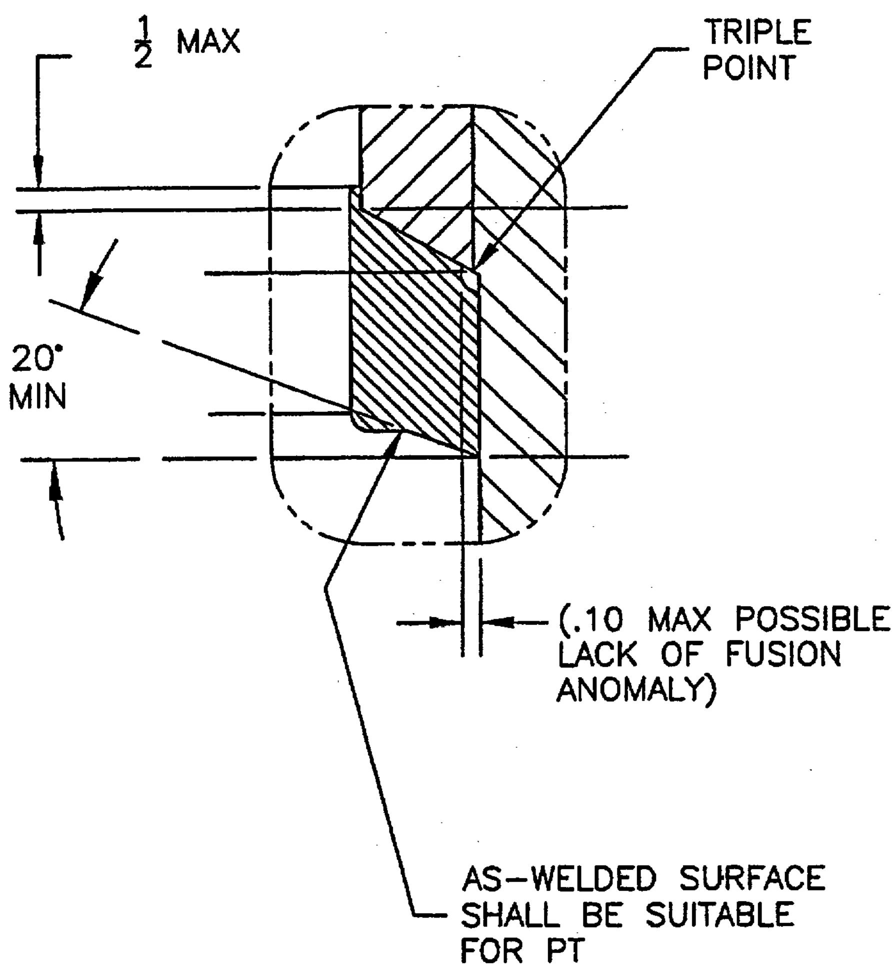


Figure 1. Weld Anomaly in Temper Bead Weld Repair

The region is called a "triple point" since three materials intersect at this location. The materials are:

a) the alloy 600 CRDM nozzle material,

b) the new ERNiCrFe-7 filler weld material,* and

c) the low alloy steel RV head material.

* Per Reference 7, Specification 5.14, Par. A7.4.3, "Filler metal of this classification is used for welding nickel-chromium-iron alloy (ASTM B163, B166, B167, and B168 having UNS Number N06690)." This UNS number is associated with Alloy 690 material.

3.1 Postulated Flaw

The triple point weld anomaly is assumed to be semi-circular in shape with an initial radius of 0.10", as indicated in Figure 1. It is further assumed that the anomaly extends 360° around the nozzle. Three flaws are postulated to simulate various orientations and propagation directions for the anomaly. A circumferential flaw and an axial flaw on the outside surface of nozzle would both propagate in a horizontal direction toward the inside surface. A cylindrically oriented flaw along the interface between the weld and head would propagate downward between the two components. The horizontal and vertical flaw propagation directions are represented in Figure 2 by separate paths for the downhill and uphill sides of the nozzle, as discussed below. For both these directions, fatigue crack growth will be calculated considering the most susceptible material for flaw propagation.

Horizontal Direction (Paths 1 and 2):

Flaw propagation is across the CRDM tube wall thickness from the OD of the tube to the ID of the tube. This is the shortest path through the component wall, passing through the new Alloy 690 weld material. However, Alloy 600 tube material properties or equivalent are used to ensure that another potential path through the HAZ between the new repair weld and the Alloy 600 tube material is bounded.

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

Vertical Direction (Paths 3 and 4):

Flaw propagation is down the outside surface of the repair weld between the weld and RV head. A continuous surface flaw is postulated to lie along this cylindrical interface between the two materials. This flaw, driven by radial stresses, may propagate along either the new Alloy 690 weld material or the low alloy steel head material.

4.0 MATERIAL PROPERTIES

The region of interest for the present flaw evaluations is at the triple point, where three different materials intersect. These materials are the CRDM nozzle material, the new weld material and the reactor vessel head material.

The Point Beach Unit 1 CRDM nozzles are made from Alloy 600 material to ASME specification SB-167 for tubular products (Reference 2). The new weld, as noted in Section 3.0, is made from Alloy 690 type material. The portion of the reactor vessel head that contains the CRDM nozzles is fabricated from SA-302 Grade B (Reference 2).

4.1 Yield Strength

Values of yield strength, S_y, are obtained from the 1989 Edition of the ASME Code (Reference 9), as listed below.

SA-302 Grade B Low Alloy Steel Plate Material (RV Head)

Room temperature	50.0 ksi
Operating temperature of 600 °F	43.8 ksi

SB-163 Material N06690 (used for Alloy 52 Weld Metal)

Room temperature	40.0 ksi
Operating temperature of 600 °F	31.1 ksi

SB-167 Material N06600 (Alloy 600 Material)

Room temperature	35.0 ksi
Operating temperature of 600 °F	27.9 ksi

4.2 Fracture Toughness

4.2.1. Low Alloy Steel RV Head Material

The fracture toughness curve in Figure A-4200-1 of Reference 3 will be used for SA-302 Grade B material. This curve is specifically applicable to SA-533 Grade B Class 1 plate material and SA-508 Class 2 and 3 forging material [3]. Welding Research Council Bulletin 175 [4] states that this curve may also be used for other steels as long as the specified minimum yield strength does not exceed 50 ksi. It is therefore appropriate to use the Section XI curve to represent the fracture toughness of the Point Beach Unit 1 SA-302 Grade B reactor vessel head.

At an operating temperature of about 600 °F, the K_{Ia} fracture toughness value for this material (using an assumed RT_{NDT} of 60 °F) is above 200 ksi$\sqrt{\text{in}}$. An upper bound value of 200 ksi$\sqrt{\text{in}}$ will be conservatively used for the present flaw evaluations.

4.2.2. Alloy 600 and Alloy 690 Materials

In Table 7 of Reference 12, Mills provides fracture toughness data for unirradiated Alloy 600 material at 24 °C (75 °F) and 427 °C (800 °F) in the form of crack initiation values for the J-integral, J_c. Using linear interpolation and the LEFM plane strain relationship between J_c and fracture toughness, K_{Jc},

$$K_{Jc} = \sqrt{\frac{J_c E}{1-\nu^2}},$$

the fracture toughness at an operating temperature of 600 °F is derived as follows:

Note: $\nu = 0.3$
1 kN/m = 1 kN/m ÷ 4.448 N/lb × 0.0254 m/in = 0.00571 kip/in

Temp. (F)	Mills [12] J_c (kN/m)	J_c (kip/in)	Code [9] E (ksi)	K_{Jc} (ksi$\sqrt{\text{in}}$)
75	382	2.18	31000	273
600	522	2.98	28700	307
800	575	3.28	27600	316

Since brittle fracture is not a credible failure mechanism for ductile materials like Alloy 600 or Alloy 690, these fracture toughness measures, provided for information only, are not considered in the present flaw evaluations. However it should be noted that the fracture toughness measures of these ductile materials is significantly greater than the fracture toughness measure of the low alloy RV head material reported in Section 4.2.1.

4.3 Fatigue Crack Growth

Flaw growth due to fatigue is characterized by

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

where C_o and n are constants that depend on the material and environmental conditions, ΔK_I is the range of applied stress intensity factor in terms of ksi$\sqrt{\text{in}}$, and da/dN is the incremental flaw growth in terms of inches/cycle. For the embedded weld anomaly considered in the present analysis, it is appropriate to use crack growth rates for an air environment. Fatigue crack growth is also dependent on the ratio of the minimum to the maximum stress intensity factor; i.e.,

$$R = (K_I)_{min} / (K_I)_{max}$$

<u>SA-302 Grade B Low Alloy Steel Plate Material (RV Head)</u>

From Article A-4300 of the 1998 Edition of Section XI with addenda through 2000 (Reference 3), the fatigue crack growth constants for subsurface flaws in an air environment are:

$$n = 3.07$$

$$C_o = 1.99 \times 10^{-10}\, S$$

where $S = 25.72\,(2.88 - R)^{-3.07}$ for $0 \leq R \leq 1$

<u>Alloy 600 and Alloy 690 Materials (used for Alloy 52 Weld Metal)</u>

Fatigue crack growth rates for austenitic stainless steels are used to predict flaw growth in the these nickel-chromium-iron components. From Article C-3210 of the 1998 Edition of Section XI with addenda through 2000 (Reference 3), the fatigue crack growth constants for subsurface flaws in an air environment are:

$$n = 3.3$$

$$C_o = C \times S$$

where $C = 10^{[-10.009 + 8.12E\text{-}4 \times T - 1.13E\text{-}6 \times T^2 + 1.02E\text{-}9 \times T^3]}$

$S = 1.0$ for $R \leq 0$

$= 1.0 + 1.8R$ for $0 < R \leq 0.79$

$= -43.35 + 57.97R$ for $0.79 < R < 1.0$

5.0 APPLIED STRESSES

The applied stresses are the cyclic stresses that contribute to fatigue crack growth. Fatigue stresses are obtained from a CRDM temper bead design stress analysis (Reference 6) that considered seven transient loading conditions:

Stress Table	Transient	Occurrences in 40 years
1	Heatup and Cooldown	200 cycles
2	Plant Loading and Unloading	3,000 cycles*
3	10% Step Load Changes	2,000 cycles
4	50% Step Load Reduction	200 cycles
5	Reactor Trip	400 cycles
6	Loss of Flow	80 cycles
7	Loss of Load	80 cycles

* Based on a realistic estimate of plant loading and unloading cycles for a non-load following plant.

To simplify the present flaw evaluations while minimizing conservatism, these transients will be grouped into three sets, as listed below. The bounding stresses for the remaining transients (after heatup/cooldown and plant loading/unloading) will be used to conservatively represent these additional cyclic loads.

Group	Transient	Cycles / 40 Years	Cycles / Year
1	Heatup and Cooldown	200	5
2	Plant Loading and Unloading	3,000	75
3	Remaining Transients	2,760	69

Stresses are available from Reference 6 for the four crack propagation paths illustrated in Figure 2. Paths 1 and 3 are located on the downhill (0°) side of the nozzle and Paths 2 and 4 are on the uphill (180°) side. Stresses are reported in a cylindrical coordinate system relative to the CRDM nozzle and include the three component directions (axial, hoop and radial) needed to calculate mode I stress intensity factors for the various postulated flaws. Stresses are provided at four uniform increments along each propagation path.

The length of Paths 1 and 2 is 0.5195" and the lengths of Paths 3 and 4 are 1.4513" (downhill side) and 0.9814" (uphill side), respectively. These path lengths are from a finite element model of an earlier design where the inside surface of the weld was remediated. The horizontal distance between the triple point and the machined weld surface in the present design is

$$(4.000" - 2.818") / 2 = 0.591" \qquad \text{(Reference 1)}$$

Since the actual weld thickness is greater than the analyzed thickness, it is conservative to use the Reference 6 stresses in the present flaw evaluations.

The "vertical" propagation paths extend from the triple point location to the lower portion of the weld at the surface of the enlarged (4.250") bore. As such, the line is slightly offset from the vertical. It may still be used, however, to represent stresses along this potential propagation path between the weld and head. On the downhill side, Path 3 extends all the way to the bottom of the weld. On the uphill side, Path 4 extends only to the top of the J-groove weld prep (top of butter) since no credit is taken for the integrity of the new-to-old weld overlap in the structural model.

Since stresses are generally higher on the uphill side of the nozzle and the length of Path 4 is less than Path 3 (smaller distance to form a potential leak path), the stresses for Paths 2 and 4 will be used to evaluate postulated flaws at the triple point weld anomaly.

This figure is not pertinent to this document.
[signature] 7/25/03
(for legibility concerns)

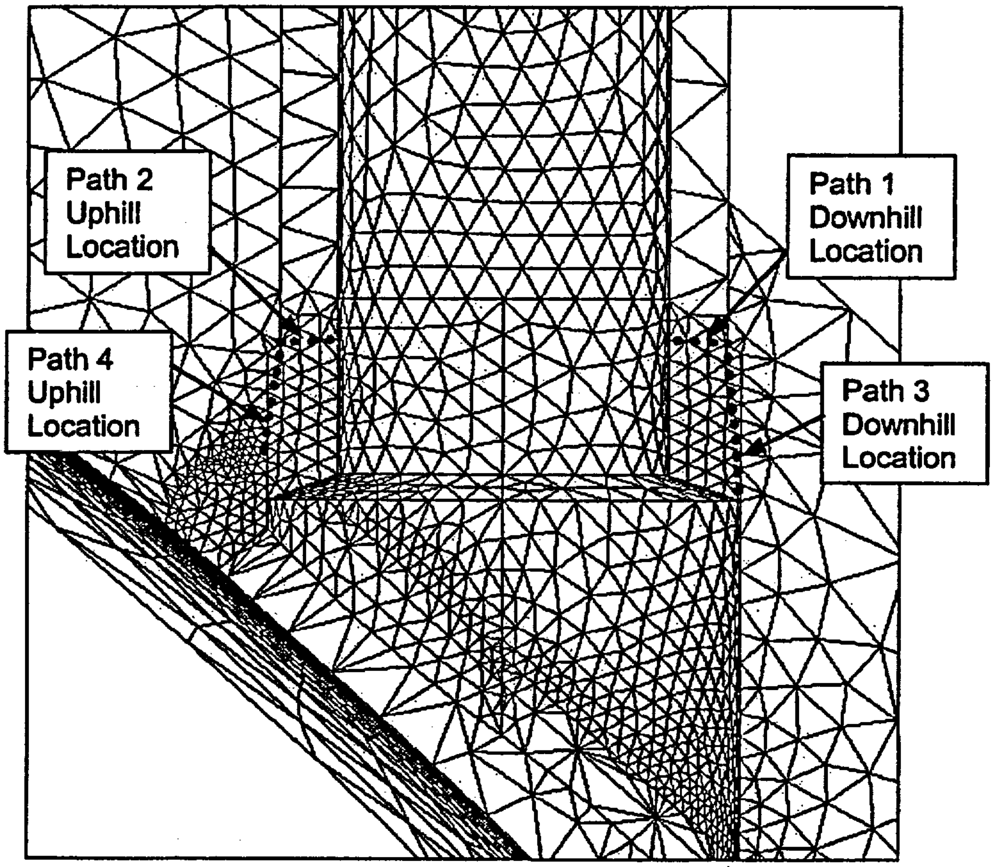


Figure 2. Illustration of Crack Propagation Paths on the Finite Element Stress Model

Table 1. Stresses for Heatup and Cooldown (from Reference 6)

Horizontal Flaw Propagation Paths

Triple Point Location

Path No: PATH1 Length= 0.51953

Location:		0.0	0.0	0.0	0.12988	0.12988	0.12988	0.25976	0.25976	0.25976	0.38965	0.38965	0.38965	0.51953	0.51953	0.51953
	Time	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--
1	0.001															
2	2															
3	4.4															
4	6															
5	7.8549															
6	8.6															
7	10.4															

Path No: PATH2 Length= 0.51953

Location:		0.0	0.0	0.0	0.12988	0.12988	0.12988	0.25976	0.25976	0.25976	0.38965	0.38965	0.38965	0.51953	0.51953	0.51953
	Time	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--
1	0.001															
2	2															
3	4.4															
4	6															
5	7.8549															
6	8.6															
7	10.4															

Triple Point Location

Vertical Flaw Propagation Paths

Path No: PATH3 Length= 1.4513

Location:		0.0	0.0	0.0	0.36283	0.36283	0.36283	0.72565	0.72565	0.72565	1.0885	1.0885	1.0885	1.4513	1.4513	1.4513
	Time	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--
1	0.001															
2	2															
3	4.4															
4	6															
5	7.8549															
6	8.6															
7	10.4															

Path No: PATH4 Length= 0.98139

Location:		0.0	0.0	0.0	0.24535	0.24535	0.24535	0.4907	0.4907	0.4907	0.73604	0.73604	0.73604	0.98139	0.98139	0.98139
	Time	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--
1	0.001															
2	2															
3	4.4															
4	6															
5	7.8549															
6	8.6															
7	10.4															

Legend for stress indicators: SX = radial stress SY = hoop stress SZ = axial stress

Table 2. Stresses for Plant Loading and Unloading (from Reference 6)

Horizontal Flaw Propagation Paths

Triple Point Location

Path No: PATH1 Length= 0.51953

Location:	0.0	0.0	0.0	0.12988	0.12988	0.12988	0.25976	0.25976	0.25976	0.38965	0.38965	0.38965	0.51953	0.51953	0.51953
Time	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--
1 0.001															
2 0.3333															
3 3															
4 3.3333															

Path No: PATH2 Length= 0.51953

Location:	0.0	0.0	0.0	0.12988	0.12988	0.12988	0.25976	0.25976	0.25976	0.38965	0.38965	0.38965	0.51953	0.51953	0.51953
Time	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--
1 0.001															
2 0.3333															
3 3															
4 3.3333															

Triple Point Location

Vertical Flaw Propagation Paths

Path No: PATH3 Length= 1.4513

Location:	0.0	0.0	0.0	0.36283	0.36283	0.36283	0.72565	0.72565	0.72565	1.0885	1.0885	1.0885	1.4513	1.4513	1.4513
Time	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--
1 0.001															
2 0.3333															
3 3															
4 3.3333															

Path No: PATH4 Length= 0.98139

Location:	0.0	0.0	0.0	0.24535	0.24535	0.24535	0.4907	0.4907	0.4907	0.73604	0.73604	0.73604	0.98139	0.98139	0.98139
Time	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--
1 0.001															
2 0.3333															
3 3															
4 3.3333															

Legend for stress indicators: SX = radial stress
SY = hoop stress
SZ = axial stress

Table 3. Stresses for 10% Step Load Changes (from Reference 6)

Horizontal Flaw Propagation Paths

Triple Point Location

Path No: PATH1 Length= 0.51953

Location:		0.0	0.0	0.0	0.12988	0.12988	0.12988	0.25976	0.25976	0.25976	0.38965	0.38965	0.38965	0.51953	0.51953	0.51953
	Time	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--
1	0.001															
2	0.027778															
3	0.0625															
4	1															
5	1.025															

Path No: PATH2 Length= 0.51953

Location:		0.0	0.0	0.0	0.12988	0.12988	0.12988	0.25976	0.25976	0.25976	0.38965	0.38965	0.38965	0.51953	0.51953	0.51953
	Time	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--
1	0.001															
2	0.027778															
3	0.0625															
4	1															
5	1.025															

Triple Point Location

Vertical Flaw Propagation Paths

Path No: PATH3 Length= 1.4513

Location:		0.0	0.0	0.0	0.36283	0.36283	0.36283	0.72565	0.72565	0.72565	1.0885	1.0885	1.0885	1.4513	1.4513	1.4513
	Time	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--
1	0.001															
2	0.027778															
3	0.0625															
4	1															
5	1.025															

Path No: PATH4 Length= 0.98139

Location:		0.0	0.0	0.0	0.24535	0.24535	0.24535	0.4907	0.4907	0.4907	0.73604	0.73604	0.73604	0.98139	0.98139	0.98139
	Time	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--
1	0.001															
2	0.027778															
3	0.0625															
4	1															
5	1.025															

Legend for stress indicators: SX = radial stress
SY = hoop stress
SZ = axial stress

Table 4. Stresses for 50% Step Load Reduction (from Reference 6)

Horizontal Flaw Propagation Paths

Triple Point Location (last three columns)

Path No: PATH1 Length= 0.51953

Location:		0.0	0.0	0.0	0.12988	0.12988	0.12988	0.25976	0.25976	0.25976	0.38965	0.38965	0.38965	0.51953	0.51953	0.51953
	Time	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--
1	0.001															
2	0.05															
3	0.23333															

Path No: PATH2 Length= 0.51953

Location:		0.0	0.0	0.0	0.12988	0.12988	0.12988	0.25976	0.25976	0.25976	0.38965	0.38965	0.38965	0.51953	0.51953	0.51953
	Time	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--
1	0.001															
2	0.05															
3	0.23333															

Vertical Flaw Propagation Paths

Triple Point Location (first three columns)

Path No: PATH3 Length= 1.4513

Location:		0.0	0.0	0.0	0.36283	0.36283	0.36283	0.72565	0.72565	0.72565	1.0885	1.0885	1.0885	1.4513	1.4513	1.4513
	Time	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--
1	0.001															
2	0.05															
3	0.23333															

Path No: PATH4 Length= 0.98139

Location:		0.0	0.0	0.0	0.24535	0.24535	0.24535	0.4907	0.4907	0.4907	0.73604	0.73604	0.73604	0.98139	0.98139	0.98139
	Time	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--
1	0.001															
2	0.05															
3	0.23333															

Legend for stress indicators: SX = radial stress
SY = hoop stress
SZ = axial stress

Table 5. Stresses for Reactor Trip (from Reference 6)

Horizontal Flaw Propagation Paths

Triple Point Location

Path No: PATH1 Length= 0.51953

Location:		0.0	0.0	0.0	0.12988	0.12988	0.12988	0.25976	0.25976	0.25976	0.38965	0.38965	0.38965	0.51953	0.51953	0.51953
	Time	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--
1	0.001															
2	0.016667															
3	0.025															

Path No: PATH2 Length= 0.51953

Location:		0.0	0.0	0.0	0.12988	0.12988	0.12988	0.25976	0.25976	0.25976	0.38965	0.38965	0.38965	0.51953	0.51953	0.51953
	Time	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--
1	0.001															
2	0.016667															
3	0.025															

Triple Point Location

Vertical Flaw Propagation Paths

Path No: PATH3 Length= 1.4513

Location:		0.0	0.0	0.0	0.36283	0.36283	0.36283	0.72565	0.72565	0.72565	1.0885	1.0885	1.0885	1.4513	1.4513	1.4513
	Time	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--
1	0.001															
2	0.016667															
3	0.025															

Path No: PATH4 Length= 0.98139

Location:		0.0	0.0	0.0	0.24535	0.24535	0.24535	0.4907	0.4907	0.4907	0.73604	0.73604	0.73604	0.98139	0.98139	0.98139
	Time	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--
1	0.001															
2	0.016667															
3	0.025															

Legend for stress indicators: SX = radial stress
SY = hoop stress
SZ = axial stress

Table 6. Stresses for Loss of Flow (from Reference 6)

Horizontal Flaw Propagation Paths

Triple Point Location

Path No: PATH1 Length= 0.51953

Location:		0.0	0.0	0.0	0.12988	0.12988	0.12988	0.25976	0.25976	0.25976	0.38965	0.38965	0.38965	0.51953	0.51953	0.51953
	Time	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--
1	0.001															
2	0.006667															
3	0.04034															

Path No: PATH2 Length= 0.51953

Location:		0.0	0.0	0.0	0.12988	0.12988	0.12988	0.25976	0.25976	0.25976	0.38965	0.38965	0.38965	0.51953	0.51953	0.51953
	Time	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--
1	0.001															
2	0.006667															
3	0.04034															

Triple Point Location

Vertical Flaw Propagation Paths

Path No: PATH3 Length= 1.4513

Location:		0.0	0.0	0.0	0.36283	0.36283	0.36283	0.72565	0.72565	0.72565	1.0885	1.0885	1.0885	1.4513	1.4513	1.4513
	Time	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--
1	0.001															
2	0.006667															
3	0.04034															

Path No: PATH4 Length= 0.98139

Location:		0.0	0.0	0.0	0.24535	0.24535	0.24535	0.4907	0.4907	0.4907	0.73604	0.73604	0.73604	0.98139	0.98139	0.98139
	Time	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--
1	0.001															
2	0.006667															
3	0.04034															

Legend for stress indicators: SX = radial stress
SY = hoop stress
SZ = axial stress

Table 7. Stresses for Loss of Load (from Reference 6)

Horizontal Flaw Propagation Paths

Triple Point Location (at 0.51953)

Path No: PATH1 Length= 0.51953

Location:		0.0	0.0	0.0	0.12988	0.12988	0.12988	0.25976	0.25976	0.25976	0.38965	0.38965	0.38965	0.51953	0.51953	0.51953
	Time	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--
1	0.001															
2	0.002778															
3	0.04444															

Path No: PATH2 Length= 0.51953

Location:		0.0	0.0	0.0	0.12988	0.12988	0.12988	0.25976	0.25976	0.25976	0.38965	0.38965	0.38965	0.51953	0.51953	0.51953
	Time	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--
1	0.001															
2	0.002778															
3	0.04444															

Vertical Flaw Propagation Paths

Triple Point Location (at 0.0)

Path No: PATH3 Length= 1.4513

Location:		0.0	0.0	0.0	0.36283	0.36283	0.36283	0.72565	0.72565	0.72565	1.0885	1.0885	1.0885	1.4513	1.4513	1.4513
	Time	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--
1	0.001															
2	0.002778															
3	0.04444															

Path No: PATH4 Length= 0.98139

Location:		0.0	0.0	0.0	0.24535	0.24535	0.24535	0.4907	0.4907	0.4907	0.73604	0.73604	0.73604	0.98139	0.98139	0.98139
	Time	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--	--SX--	--SY--	--SZ--
1	0.001															
2	0.002778															
3	0.04444															

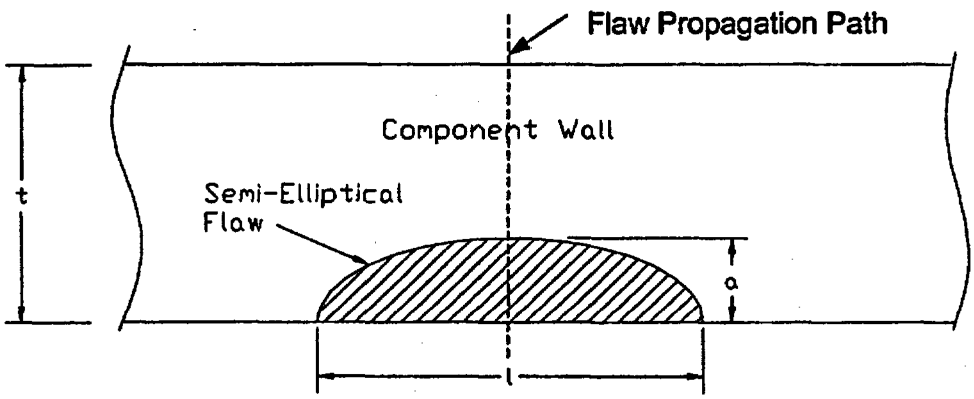
Legend for stress indicators: SX = radial stress
SY = hoop stress
SZ = axial stress

6.0 FRACTURE MECHANICS METHODOLOGY

This section presents several aspects of linear elastic fracture mechanics (LEFM) and limit load analysis (to address the ductile Alloy 600 and Alloy 690 materials) that form the basis of the present flaw evaluations. As discussed in Section 3.1, flaw evaluations are performed for flaw propagation Paths 2 and 4 in Figure 2.

Path 2 represents a section across the new Alloy 52 weld metal which is equivalent to the thickness of the CRDM tube wall. Since the weld anomaly is located at the base of the OD of the CRDM tube and is assumed to be all the way around the circumference, a stress intensity factor (SIF) solution for a 360 degree circumferential crack on the OD of a circular tube is deemed appropriate. Therefore, the SIF solution of Buchalet and Bamford (Reference 13) is used in the analysis. However, this solution is applicable for a 360-degree part-through ID flaw. To develop an SIF solution for a 360 degree part-through OD flaw, an F function is determined based on SIF solutions of Kumar (References 14 and 15). The appropriate F function for an internal as well as an external circumferential flaw in a cylinder subjected to remote tension are determined first. The ratio of the F functions of the external flaw to the internal flaw is considered to be the appropriate multiplication factor for the Buchalet and Bamford SIF solution, to extend its application to an external crack. The materials to be considered for this path are the Alloy 600 tube material or the Alloy 52 weld metal. A limit load analysis for an external circumferential flaw in a cylinder subjected to remote tension (Reference 15) is also performed for applied loads on the CRDM tube.

An axially oriented semi-circular OD surface flaw is also considered in the evaluation, as illustrated by the schematic below.



where, a = initial flaw depth = 0.100 inch

$l = 2c$ = flaw length = 0.200 inch

t = wall thickness = 0.591 inch

An axial flaw is considered since the stresses in the CRDM penetration region are primarily due to pressure and therefore the hoop stresses are more significant. The SIF solution by Raju & Newman (Reference 10) for an external surface crack in a cylindrical vessel is used in the evaluation. The fatigue flaw growth analysis for the axial crack is also performed using the austenitic stainless steel properties.

The Irwin plasticity correction is also considered in the SIF solutions discussed above. This plastic zone correction is discussed in detail in Section 2.8.1 of Reference 11. The effective crack length is defined as the sum of the actual crack size and the plastic zone correction:

$$a_e = a + r_y$$

where r_y for plane strain conditions (applicable for this analysis) is given by:

$$r_y = \frac{1}{6\pi}\left(\frac{K_I}{\sigma_{YS}}\right)^2$$

Path 4 represents the interface between the new repair weld and the RV head material. The potential for flaw propagation along this interface is likely if radial stresses are significant between the weld and head. This assessment utilizes an SIF solution for a continuous surface crack in a flat plate from Appendix A of Section XI (Reference 3). Crack growth analysis is performed considering propagation through the Alloy 52 weld metal or the low alloy steel head material, whichever is limiting.

7.0 ACCEPTANCE CRITERIA

For low alloy steel materials such as the reactor vessel head material, the evaluation will be performed to the IWB-3612 acceptance criteria of Section XI of the Code (Reference 3). The following considerations are made to address the flaw acceptance criteria for highly ductile materials such as Alloy 600 and Alloy 690 type materials. The initial flaw depth to thickness ratio for the postulated weld anomaly is about 20%. Fatigue crack growth is minimal for Alloy 600 or Alloy 690 materials in an air environment. The only acceptance criterion on flaw size is the industry developed 75% through-wall limit on depth (Reference 8):

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

For the shallow cracks considered in the present analysis, this criterion is easily met.

Another acceptance criterion for ductile materials is demonstration of sufficient limit load margin. From IWB-3642 (Reference 3), the required safety margin, based on load, is a factor of 3 for normal and upset operating conditions. Stress intensity factors are also evaluated considering the required fracture toughness margin of $\sqrt{10}$ for normal and upset operating conditions.

8.0 FLAW EVALUATIONS

The evaluation of the postulated external circumferential flaw for propagation along Path 2 is contained in Tables 8 and 9. The fatigue crack growth analysis is provided in Table 8 and a limit load analysis is presented in Table 9.

The evaluation of an external axial flaw for fatigue crack growth along Path 2 is contained in Table 10.

A continuous surface flaw between the repair weld and the RV head is analyzed for fatigue crack growth along Path 4 in Table 11.

The fatigue crack growth analyses (in Tables 8, 10, and 11) uniformly distribute the applied cycles over the 25 year service life by linking the incremental crack growth due to various loading conditions.

Table 8. Evaluation of Continuous External Circumferential Flaw for Fatigue Crack Growth Along Path 2

INPUT DATA

Geometry:	Outside diameter,	Do =	4.000	in.
	Inside diameter,	Di =	2.818	in.
	Thickness,	t =	0.591	in.
		Ri/t =	2.384	
Flaw Size:	Flaw depth,	a =	0.100	in.
		a/t =	0.169	
Environment:	Temperature,	T =	600	F
Material Strength:	Yield strength,	σ_{ys} =	27.9	ksi

Table 8. Evaluation of Continuous External Circumferential Flaw for Fatigue Crack Growth Along Path 2 (Cont'd)

Variation of F Function between Continuous External and Continuous Internal Circumferential Flaws Using Solutions by V. Kumar et al.

Source: EPRI NP-1931 Topical Report, Section 4.3 for F Function for An Internal Circumferential Crack Under Remote Tension (Ref. 14).

The applied KI equation is given by the expression:

$$KI = \sigma^* \sqrt{(\pi^* a)}^* F(a/b, Ri/Ro)$$

where

$$\sigma = P/(\pi^*(Ro^2 - Ri^2)$$

and F is a function of a/b and Ri/Ro or b/Ri.

For this application:

a/b = 0.169
b/Ri = 0.419

By extrapolation from Table 4-5 of EPRI-1931, F is estimated to be:

F = 1.11

Source: GE Report SRD-82-048, Prepared for EPRI Contract RP-1237-1, Fifth & Sixth Semi-Annual Report, Section 3.5 for F Function (Ref. 15).

For the external circumferential crack, the expressions for KI and σ are as defined above for the internal circumferential crack.

From Figure 3-11, the F function for:

a/b = 0.169
Ri/Ro = 0.705

is estimated to be,

F = 1.25

Multiplying Factor:

To estimate the stress intensity factor for an external circumferential crack from the solution for an internal circumferential crack under remote tension, the appropriate multiplying factor is: 1.13

Table 8. Evaluation of Continuous External Circumferential Flaw for Fatigue Crack Growth Along Path 2 (Cont'd)

CIRCUMFERENTIAL FLAW STRESS INTENSITY FACTOR FOR HEATUP AND COOLDOWN STRESSES

Basis: Buchalet and Bamford solution for continuous circumferential flaws on the inside surface of cylinders (Ref. 13)

$$KI = \sqrt{(\pi^* a)} * [A_0 F_1 + (2a/\pi) A_1 F_2 + (a^2/2) A_2 F_3 + (4a^3)/(3\pi) A_3 F_4]$$

where,
$F1 = 1.1259 + 0.2344(a/t) + 2.2018(a/t)^2 - 0.2083(a/t)^3$
$F2 = 1.0732 + 0.2677(a/t) + 0.6661(a/t)^2 + 0.6354(a/t)^3$
$F3 = 1.0528 + 0.1065(a/t) + 0.4429(a/t)^2 + 0.6042(a/t)^3$
$F4 = 1.0387 - 0.0939(a/t) + 0.6018(a/t)^2 + 0.3750(a/t)^3$

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

$$S(x) = A_0 + A_1 x + A_2 x^2 + A_3 x^3.$$

Applicability: $Ri/t = 10$
$a/t \leq 0.8$

Axial Stresses:

Wall Position x	Normal/Upset Cond. Stresses [6]	
	SS*	Shutdown
(in.)	(ksi)	(ksi)
0.00000		
0.14775		
0.29550		
0.44325		
0.59100		

* Heatup/Cooldown transient at 6.0 hours (steady state) using stresses for Path 2

Stress Coefficients:

Stress Coeff.	Normal/Upset Loading Conditions	
	NU1	NU2
	(ksi)	(ksi)
A_0		
A_1		
A_2		
A_3		

Table 8. Evaluation of Continuous External Circumferential Flaw for Fatigue Crack Growth Along Path 2 (Cont'd)

CIRCUMFERENTIAL FLAW STRESS INTENSITY FACTOR FOR PLANT LOADING AND UNLOADING STRESSES

Basis: Buchalet and Bamford solution for continuous circumferential flaws on the inside surface of cylinders (Ref. 13)

$$KI = \sqrt{(\pi * a)} * [A_0 F_1 + (2a/\pi) A_1 F_2 + (a^2/2) A_2 F_3 + (4a^3)/(3\pi) A_3 F_4]$$

where,

$$F1 = 1.1259 + 0.2344(a/t) + 2.2018(a/t)^2 - 0.2083(a/t)^3$$
$$F2 = 1.0732 + 0.2677(a/t) + 0.6661(a/t)^2 + 0.6354(a/t)^3$$
$$F3 = 1.0528 + 0.1065(a/t) + 0.4429(a/t)^2 + 0.6042(a/t)^3$$
$$F4 = 1.0387 - 0.0939(a/t) + 0.6018(a/t)^2 + 0.3750(a/t)^3$$

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

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

Applicability: $Ri/t = 10$
$a/t \le 0.8$

Axial Stresses:

Wall Position x (in.)	Normal/Upset Cond. Stresses [6] PU* (ksi)	PL** (ksi)
0.00000		
0.14775		
0.29550		
0.44325		
0.59100		

* Plant Loading/Unloading transient at 3.333 hours (plant unloading) using stresses for Path 2

** Plant Loading/Unloading transient at 0.333 hours (plant loading) using stresses for Path 2

Stress Coefficients:

Stress Coeff.	Normal/Upset Loading Conditions NU1 (ksi)	NU2 (ksi)
A_0		
A_1		
A_2		
A_3		

Table 8. Evaluation of Continuous External Circumferential Flaw for Fatigue Crack Growth Along Path 2 (Cont'd)

CIRCUMFERENTIAL FLAW STRESS INTENSITY FACTOR FOR REMAINING TRANSIENT STRESSES

Basis: Buchalet and Bamford solution for continuous circumferential flaws on the inside surface of cylinders (Ref. 13)

$$KI = \sqrt{(\pi * a)} * [A_0 F_1 + (2a/\pi) A_1 F_2 + (a^2/2) A_2 F_3 + (4a^3)/(3\pi) A_3 F_4]$$

where,
$$F1 = 1.1259 + 0.2344(a/t) + 2.2018(a/t)^2 - 0.2083(a/t)^3$$
$$F2 = 1.0732 + 0.2677(a/t) + 0.6661(a/t)^2 + 0.6354(a/t)^3$$
$$F3 = 1.0528 + 0.1065(a/t) + 0.4429(a/t)^2 + 0.6042(a/t)^3$$
$$F4 = 1.0387 - 0.0939(a/t) + 0.6018(a/t)^2 + 0.3750(a/t)^3$$

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

$$S(x) = A_0 + A_1 x + A_2 x^2 + A_3 x^3.$$

Applicability: Ri/t = 10
$a/t \leq 0.8$

Axial Stresses:

Wall Position x	Normal/Upset Cond. Stresses [6]	
	LL1*	LL2**
(in.)	(ksi)	(ksi)
0.00000		
0.14775		
0.29550		
0.44325		
0.59100		

* Loss of Load transient at 0.00278 hours (max. stress) using stresses for Path 2

** Loss of Load transient at 0.0444 hours (min. stress) using stresses for Path 2

Stress Coefficients:

Stress Coeff.	Normal/Upset Loading Conditions	
	NU1	NU2
	(ksi)	(ksi)
A_0		
A_1		
A_2		
A_3		

Table 8. Evaluation of Continuous External Circumferential Flaw for Fatigue Crack Growth Along Path 2 (Cont'd)

CIRCUMFERENTIAL FLAW FATIGUE CRACK GROWTH FOR HEATUP AND COOLDOWN TRANSIENT

Basis: $\Delta a = \Delta N * C_o(\Delta KI)^n$

Transient frequency: 200 cycles over 40 years

$\Delta N =$ 5 cycles/year

Operating Time (yr.)	Cycle	a (in.)	NU1 KI(a)max (ksi√in)	NU2 KI(a)min (ksi√in)	ΔKI (ksi√in)	R	S	C_o	Δa (in.)	r_y	a_e	NU1 KI(a_e)max (ksi√in)
0	0	0.10000	15.68	0.00	15.68	0.00	1.00	1.96E-10	8.62E-06	0.017		16.17
1	5		15.69	0.00	15.69	0.00	1.00	1.96E-10	8.63E-06	0.017		16.18
2	10		15.69	0.00	15.69	0.00	1.00	1.96E-10	8.63E-06	0.017		16.18
3	15		15.69	0.00	15.69	0.00	1.00	1.96E-10	8.63E-06	0.017		16.18
4	20		15.69	0.00	15.69	0.00	1.00	1.96E-10	8.63E-06	0.017		16.18
5	25		15.69	0.00	15.69	0.00	1.00	1.96E-10	8.63E-06	0.017		16.18
6	30		15.69	0.00	15.69	0.00	1.00	1.96E-10	8.64E-06	0.017		16.18
7	35		15.69	0.00	15.69	0.00	1.00	1.96E-10	8.64E-06	0.017		16.18
8	40		15.69	0.00	15.69	0.00	1.00	1.96E-10	8.64E-06	0.017		16.18
9	45		15.69	0.00	15.69	0.00	1.00	1.96E-10	8.64E-06	0.017		16.18
10	50		15.69	0.00	15.69	0.00	1.00	1.96E-10	8.64E-06	0.017		16.18
11	55		15.70	0.00	15.70	0.00	1.00	1.96E-10	8.65E-06	0.017		16.18
12	60		15.70	0.00	15.70	0.00	1.00	1.96E-10	8.65E-06	0.017		16.18
13	65		15.70	0.00	15.70	0.00	1.00	1.96E-10	8.65E-06	0.017		16.19
14	70		15.70	0.00	15.70	0.00	1.00	1.96E-10	8.65E-06	0.017		16.19
15	75		15.70	0.00	15.70	0.00	1.00	1.96E-10	8.65E-06	0.017		16.19
16	80		15.70	0.00	15.70	0.00	1.00	1.96E-10	8.65E-06	0.017		16.19
17	85		15.70	0.00	15.70	0.00	1.00	1.96E-10	8.66E-06	0.017		16.19
18	90		15.70	0.00	15.70	0.00	1.00	1.96E-10	8.66E-06	0.017		16.19
19	95		15.70	0.00	15.70	0.00	1.00	1.96E-10	8.66E-06	0.017		16.19
20	100		15.71	0.00	15.71	0.00	1.00	1.96E-10	8.66E-06	0.017		16.19
21	105		15.71	0.00	15.71	0.00	1.00	1.96E-10	8.66E-06	0.017		16.19
22	110		15.71	0.00	15.71	0.00	1.00	1.96E-10	8.67E-06	0.017		16.19
23	115		15.71	0.00	15.71	0.00	1.00	1.96E-10	8.67E-06	0.017		16.19
24	120		15.71	0.00	15.71	0.00	1.00	1.96E-10	8.67E-06	0.017		16.19
25	125		15.71	0.00	15.71	0.00	1.00	1.96E-10	8.67E-06	0.017		16.20

Table 8. Evaluation of Continuous External Circumferential Flaw for Fatigue Crack Growth Along Path 2 (Cont'd)

CIRCUMFERENTIAL FLAW FATIGUE CRACK GROWTH FOR PLANT LOADING AND UNLOADING TRANSIENT

Basis: $\Delta a = \Delta N * C_o(\Delta KI)^n$

Transient frequency: 3000 cycles over 40 years

$\Delta N =$ 75 cycles/year

Operating Time (yr.)	Cycle	a (in.)	NU1 KI(a)max (ksi√in)	NU2 KI(a)min (ksi√in)	ΔKI (ksi√in)	R	S	C_o	Δa (in.)	r_y	a_e	NU1 KI(a_e)max (ksi√in)
0	0		15.26	12.38	2.88	0.81	3.68	7.20E-10	1.77E-06	0.016		15.66
1	75		15.26	12.38	2.88	0.81	3.68	7.20E-10	1.77E-06	0.016		15.66
2	150		15.26	12.38	2.88	0.81	3.68	7.20E-10	1.77E-06	0.016		15.67
3	225		15.26	12.38	2.88	0.81	3.68	7.20E-10	1.77E-06	0.016		15.67
4	300		15.26	12.38	2.88	0.81	3.68	7.21E-10	1.77E-06	0.016		15.67
5	375		15.26	12.38	2.88	0.81	3.68	7.21E-10	1.77E-06	0.016		15.67
6	450		15.26	12.38	2.88	0.81	3.68	7.21E-10	1.77E-06	0.016		15.67
7	525		15.26	12.38	2.88	0.81	3.68	7.21E-10	1.77E-06	0.016		15.67
8	600		15.26	12.38	2.88	0.81	3.68	7.21E-10	1.77E-06	0.016		15.67
9	675		15.26	12.38	2.88	0.81	3.68	7.21E-10	1.77E-06	0.016		15.67
10	750		15.27	12.39	2.88	0.81	3.68	7.21E-10	1.77E-06	0.016		15.67
11	825		15.27	12.39	2.88	0.81	3.69	7.21E-10	1.77E-06	0.016		15.67
12	900		15.27	12.39	2.88	0.81	3.69	7.21E-10	1.77E-06	0.016		15.67
13	975		15.27	12.39	2.88	0.81	3.69	7.22E-10	1.78E-06	0.016		15.67
14	1050		15.27	12.39	2.88	0.81	3.69	7.22E-10	1.78E-06	0.016		15.67
15	1125		15.27	12.39	2.88	0.81	3.69	7.22E-10	1.78E-06	0.016		15.67
16	1200		15.27	12.39	2.88	0.81	3.69	7.22E-10	1.78E-06	0.016		15.68
17	1275		15.27	12.39	2.88	0.81	3.69	7.22E-10	1.78E-06	0.016		15.68
18	1350		15.27	12.39	2.88	0.81	3.69	7.22E-10	1.78E-06	0.016		15.68
19	1425		15.27	12.39	2.88	0.81	3.69	7.22E-10	1.78E-06	0.016		15.68
20	1500		15.27	12.39	2.88	0.81	3.69	7.22E-10	1.78E-06	0.016		15.68
21	1575		15.28	12.40	2.88	0.81	3.69	7.22E-10	1.78E-06	0.016		15.68
22	1650		15.28	12.40	2.88	0.81	3.69	7.23E-10	1.78E-06	0.016		15.68
23	1725		15.28	12.40	2.88	0.81	3.69	7.23E-10	1.78E-06	0.016		15.68
24	1800		15.28	12.40	2.88	0.81	3.69	7.23E-10	1.78E-06	0.016		15.68
25	1875		15.28	12.40	2.88	0.81	3.69	7.23E-10	1.78E-06	0.016		15.68

Table 8. Evaluation of Continuous External Circumferential Flaw for Fatigue Crack Growth Along Path 2 (Cont'd)

CIRCUMFERENTIAL FLAW FATIGUE CRACK GROWTH FOR REMAINING TRANSIENTS

Basis: $\Delta a = \Delta N * C_o(\Delta KI)^n$

Transient frequency: 2760 cycles over 40 years

$\Delta N =$ 69 cycles/year

Operating Time (yr.)	Cycle	a (in.)	NU1 KI(a)max (ksi√in)	NU2 KI(a)min (ksi√in)	ΔKI (ksi√in)	R	S	C_o	Δa (in.)	r_y	a_e	NU1 KI(a_e)max (ksi√in)
0	0		17.18	9.74	7.45	0.57	2.02	3.95E-10	2.06E-05	0.020		17.86
1	69		17.18	9.74	7.45	0.57	2.02	3.95E-10	2.06E-05	0.020		17.86
2	138		17.19	9.74	7.45	0.57	2.02	3.95E-10	2.06E-05	0.020		17.86
3	207		17.19	9.74	7.45	0.57	2.02	3.95E-10	2.06E-05	0.020		17.86
4	276		17.19	9.74	7.45	0.57	2.02	3.95E-10	2.06E-05	0.020		17.86
5	345		17.19	9.74	7.45	0.57	2.02	3.95E-10	2.06E-05	0.020		17.86
6	414		17.19	9.74	7.45	0.57	2.02	3.95E-10	2.06E-05	0.020		17.86
7	483		17.19	9.74	7.45	0.57	2.02	3.95E-10	2.06E-05	0.020		17.87
8	552		17.19	9.74	7.45	0.57	2.02	3.95E-10	2.06E-05	0.020		17.87
9	621		17.19	9.74	7.45	0.57	2.02	3.95E-10	2.06E-05	0.020		17.87
10	690		17.20	9.74	7.45	0.57	2.02	3.95E-10	2.06E-05	0.020		17.87
11	759		17.20	9.74	7.46	0.57	2.02	3.95E-10	2.07E-05	0.020		17.87
12	828		17.20	9.74	7.46	0.57	2.02	3.95E-10	2.07E-05	0.020		17.87
13	897		17.20	9.74	7.46	0.57	2.02	3.95E-10	2.07E-05	0.020		17.87
14	966		17.20	9.74	7.46	0.57	2.02	3.95E-10	2.07E-05	0.020		17.87
15	1035		17.20	9.74	7.46	0.57	2.02	3.95E-10	2.07E-05	0.020		17.87
16	1104		17.20	9.74	7.46	0.57	2.02	3.95E-10	2.07E-05	0.020		17.87
17	1173		17.20	9.74	7.46	0.57	2.02	3.95E-10	2.07E-05	0.020		17.88
18	1242		17.21	9.74	7.46	0.57	2.02	3.95E-10	2.07E-05	0.020		17.88
19	1311		17.21	9.75	7.46	0.57	2.02	3.95E-10	2.07E-05	0.020		17.88
20	1380		17.21	9.75	7.46	0.57	2.02	3.95E-10	2.07E-05	0.020		17.88
21	1449		17.21	9.75	7.46	0.57	2.02	3.95E-10	2.07E-05	0.020		17.88
22	1518		17.21	9.75	7.46	0.57	2.02	3.95E-10	2.07E-05	0.020		17.88
23	1587		17.21	9.75	7.46	0.57	2.02	3.95E-10	2.07E-05	0.020		17.88
24	1656		17.21	9.75	7.46	0.57	2.02	3.95E-10	2.07E-05	0.020		17.88
25	1725		17.21	9.75	7.46	0.57	2.02	3.95E-10	2.07E-05	0.020		17.88

Table 9. Limit Load Analysis for a Continuous External Circumferenital Flaw

LIMIT LOAD

Basis: GE Report SRD-82-048, Combined Fifth and Sixth Semi-Annual Report by V. Kumar et al, Section 3.5 (Ref. 15).

For remote tension loading,

$$Po = 2/\sqrt{3}*\sigma_o*\pi*(Rc^2-Ri^2)$$

where

$Rc = Ro - a$

and

$\sigma_o =$ 27900 psi (conservatively using the minimum yield strength)

$Ro =$ [in.

$a =$ in.

$Rc =$ in.

$Ri =$] in.

Then

$Po =$ [ ] lbs

A bounding axial tube load on the CRDM tube is the hydrostatic test load:

$$P = (\pi Ri^2)*p_h$$

where

p_h = hydrostatic test pressure

= 1.25 times the design pressure

$p_d =$ [ ] psig (Ref. 2)

Then

$p_h =$ [ ] psig

and

$P =$ [ ] lbs

The limit load safety margin is:

Po/P = 8.47

This safety margin is greater than the value of 3 required by Article IWB-3642 of Section XI (Reference 3).

Table 10. Evaluation of an External Axial Flaw for Fatigue Crack Growth Along Path 2

INPUT DATA

Geometry:	Outside diameter,	Do =	4.000	in.
	Inside diameter,	Di =	2.818	in.
	Thickness,	t =	0.591	in.
		Ri/t =	2.384	
Flaw Size:	Flaw depth,	a =	0.100	in.
		a/t =	0.169	
Environment:	Temperature,	T =	600	F
Material Strength:	Yield strength,	σ_{ys} =	27.9	ksi

Table 10. Evaluation of an External Axial Flaw for Fatigue Crack Growth Along Path 2

AXIAL FLAW STRESS INTENSITY FACTOR FOR HEATUP AND COOLDOWN STRESSES

Basis: Raju & Newman, "Stress Intensity Factors for Internal & External Surface Cracks in Cylindrical Vessels (Ref. 10)

$$KI = \sqrt{(\pi/Q)} * [G_0 A_0 a^{0.5} + G_1 A_1 a^{1.5} + G_2 A_2 a^{2.5} + G_3 A_3 a^{3.5}]$$

where, per Table 4, for an external surface crack and for t/R = 0.25, a/t = 0.2, $2\phi/\pi = 1$, and a/c = 1.0

Go = 1.030
G_1 = 0.720
G_2 = 0.591
G_3 = 0.513

and Q = 2.464 = (1 + 1.464*(a/c)^1.65)

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

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

Hoop Stresses:

Wall Position x	Normal/Upset Cond. Stresses [6]	
	SS*	Shutdown
(in.)	(ksi)	(ksi)
0.00000		
0.14775		
0.29550		
0.44325		
0.59100		

* Heatup/Cooldown transient at 6.0 hours (steady state) using stresses for Path 2

Stress Coefficients:

Stress Coeff.	Normal/Upset Loading Conditions	
	NU1	NU2
	(ksi)	(ksi)
A_0		
A_1		
A_2		
A_3		

Table 10. Evaluation of an External Axial Flaw for Fatigue Crack Growth Along Path 2

AXIAL FLAW STRESS INTENSITY FACTOR FOR PLANT LOADING AND UNLOADING STRESSES

Basis: Raju & Newman, "Stress Intensity Factors for Internal & External Surface Cracks in Cylindrical Vessels (Ref. 10)

$$KI = \sqrt{(\pi/Q)} * [G_0 A_0 a^{0.5} + G_1 A_1 a^{1.5} + G_2 A_2 a^{2.5} + G_3 A_3 a^{3.5}]$$

where, per Table 4, for an external surface crack and for t/R = 0.25, a/t = 0.2, $2\phi/\pi = 1$, and a/c = 1.0

Go = 1.030
G_1 = 0.720
G_2 = 0.591
G_3 = 0.513

and Q = 2.464 = (1 + 1.464*(a/c)^1.65)

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

$$S(x) = A_0 + A_1 x + A_2 x^2 + A_3 x^3.$$

Hoop Stresses:

Wall Position x	Normal/Upset Cond. Stresses [6]	
	PU*	PL**
(in.)	(ksi)	(ksi)
0.00000		
0.14775		
0.29550		
0.44325		
0.59100		

* Plant Loading/Unloading transient at 3.333 hours (plant unloading) using stresses for Path 2

** Plant Loading/Unloading transient at 0.333 hours (plant loading) using stresses for Path 2

Stress Coefficients:

Stress Coeff.	Normal/Upset Loading Conditions	
	NU1	NU2
	(ksi)	(ksi)
A_0		
A_1		
A_2		
A_3		

Table 10. Evaluation of an External Axial Flaw for Fatigue Crack Growth Along Path 2

AXIAL FLAW STRESS INTENSITY FACTOR FOR REMAINING TRANSIENT STRESSES

Basis: Raju & Newman, "Stress Intensity Factors for Internal & External Surface Cracks in Cylindrical Vessels (Ref. 10)

$$KI = \sqrt{(\pi/Q)} * [G_0 A_0 a^{0.5} + G_1 A_1 a^{1.5} + G_2 A_2 a^{2.5} + G_3 A_3 a^{3.5}]$$

where, per Table 4, for an external surface crack and for t/R = 0.25, a/t = 0.2, $2\phi/\pi$ = 1, and a/c = 1.0

G_o = 1.030
G_1 = 0.720
G_2 = 0.591
G_3 = 0.513

and Q = 2.464 = (1 + 1.464*(a/c)^1.65)

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

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

Hoop Stresses:

Wall Position x	Normal/Upset Cond. Stresses [6]	
	LL1*	LL2**
(in.)	(ksi)	(ksi)
0.00000		
0.14775		
0.29550		
0.44325		
0.59100		

* Loss of Load transient at 0.00278 hours (max. stress) using stresses for Path 2

** Loss of Load transient at 0.0444 hours (min. stress) using stresses for Path 2

Stress Coefficients:

Stress Coeff.	Normal/Upset Loading Conditions	
	NU1	NU2
	(ksi)	(ksi)
A_0		
A_1		
A_2		
A_3		

Table 10. Evaluation of an External Axial Flaw for Fatigue Crack Growth Along Path 2 (Cont'd)

AXIAL FLAW FATIGUE CRACK GROWTH FOR HEATUP AND COOLDOWN TRANSIENT

Basis: $\Delta a = \Delta N * C_o(\Delta KI)^n$

Transient frequency: 200 cycles over 40 years

ΔN = 5 cycles/year

Operating Time (yr.)	Cycle	a (in.)	NU1 KI(a)max (ksi√in)	NU2 KI(a)min (ksi√in)	ΔKI (ksi√in)	R	S	C_o	Δa (in.)	r_y	a_e	NU1 KI(a_e)max (ksi√in)
0	0	0.10000	13.79	0.00	13.79	0.00	1.00	1.96E-10	5.64E-06	0.013		14.44
1	5		13.80	0.00	13.80	0.00	1.00	1.96E-10	5.65E-06	0.013		14.44
2	10		13.80	0.00	13.80	0.00	1.00	1.96E-10	5.65E-06	0.013		14.44
3	15		13.80	0.00	13.80	0.00	1.00	1.96E-10	5.65E-06	0.013		14.44
4	20		13.80	0.00	13.80	0.00	1.00	1.96E-10	5.65E-06	0.013		14.45
5	25		13.80	0.00	13.80	0.00	1.00	1.96E-10	5.65E-06	0.013		14.45
6	30		13.80	0.00	13.80	0.00	1.00	1.96E-10	5.65E-06	0.013		14.45
7	35		13.80	0.00	13.80	0.00	1.00	1.96E-10	5.66E-06	0.013		14.45
8	40		13.80	0.00	13.80	0.00	1.00	1.96E-10	5.66E-06	0.013		14.45
9	45		13.80	0.00	13.80	0.00	1.00	1.96E-10	5.66E-06	0.013		14.45
10	50		13.80	0.00	13.80	0.00	1.00	1.96E-10	5.66E-06	0.013		14.45
11	55		13.81	0.00	13.81	0.00	1.00	1.96E-10	5.66E-06	0.013		14.45
12	60		13.81	0.00	13.81	0.00	1.00	1.96E-10	5.66E-06	0.013		14.45
13	65		13.81	0.00	13.81	0.00	1.00	1.96E-10	5.66E-06	0.013		14.45
14	70		13.81	0.00	13.81	0.00	1.00	1.96E-10	5.67E-06	0.013		14.46
15	75		13.81	0.00	13.81	0.00	1.00	1.96E-10	5.67E-06	0.013		14.46
16	80		13.81	0.00	13.81	0.00	1.00	1.96E-10	5.67E-06	0.013		14.46
17	85		13.81	0.00	13.81	0.00	1.00	1.96E-10	5.67E-06	0.013		14.46
18	90		13.81	0.00	13.81	0.00	1.00	1.96E-10	5.67E-06	0.013		14.46
19	95		13.81	0.00	13.81	0.00	1.00	1.96E-10	5.67E-06	0.013		14.46
20	100		13.82	0.00	13.82	0.00	1.00	1.96E-10	5.67E-06	0.013		14.46
21	105		13.82	0.00	13.82	0.00	1.00	1.96E-10	5.68E-06	0.013		14.46
22	110		13.82	0.00	13.82	0.00	1.00	1.96E-10	5.68E-06	0.013		14.46
23	115		13.82	0.00	13.82	0.00	1.00	1.96E-10	5.68E-06	0.013		14.47
24	120		13.82	0.00	13.82	0.00	1.00	1.96E-10	5.68E-06	0.013		14.47
25	125		13.82	0.00	13.82	0.00	1.00	1.96E-10	5.68E-06	0.013		14.47

Table 10. Evaluation of an External Axial Flaw for Fatigue Crack Growth Along Path 2 (Cont'd)

AXIAL FLAW FATIGUE CRACK GROWTH FOR PLANT LOADING AND UNLOADING TRANSIENT

Basis: $\Delta a = \Delta N * C_o(\Delta KI)^n$

Transient frequency: 3000 cycles over 40 years

$\Delta N =$ 75 cycles/year

Operating Time (yr.)	Cycle	a (in.)	NU1 KI(a)max (ksi√in)	NU2 KI(a)min (ksi√in)	ΔKI (ksi√in)	R	S	C_o	Δa (in.)	r_y	a_e	NU1 KI(a_e)max (ksi√in)
0	0		14.01	10.15	3.87	0.72	2.30	4.51E-10	2.93E-06	0.013		14.73
1	75		14.02	10.15	3.87	0.72	2.30	4.51E-10	2.93E-06	0.013		14.73
2	150		14.02	10.15	3.87	0.72	2.30	4.51E-10	2.93E-06	0.013		14.73
3	225		14.02	10.15	3.87	0.72	2.30	4.51E-10	2.93E-06	0.013		14.73
4	300		14.02	10.15	3.87	0.72	2.30	4.51E-10	2.93E-06	0.013		14.73
5	375		14.02	10.15	3.87	0.72	2.30	4.51E-10	2.93E-06	0.013		14.73
6	450		14.02	10.15	3.87	0.72	2.30	4.51E-10	2.94E-06	0.013		14.73
7	525		14.02	10.15	3.87	0.72	2.30	4.51E-10	2.94E-06	0.013		14.73
8	600		14.02	10.16	3.87	0.72	2.30	4.51E-10	2.94E-06	0.013		14.74
9	675		14.02	10.16	3.87	0.72	2.30	4.51E-10	2.94E-06	0.013		14.74
10	750		14.03	10.16	3.87	0.72	2.30	4.51E-10	2.94E-06	0.013		14.74
11	825		14.03	10.16	3.87	0.72	2.30	4.51E-10	2.94E-06	0.013		14.74
12	900		14.03	10.16	3.87	0.72	2.30	4.51E-10	2.94E-06	0.013		14.74
13	975		14.03	10.16	3.87	0.72	2.30	4.51E-10	2.94E-06	0.013		14.74
14	1050		14.03	10.16	3.87	0.72	2.30	4.51E-10	2.94E-06	0.013		14.74
15	1125		14.03	10.16	3.87	0.72	2.30	4.51E-10	2.94E-06	0.013		14.74
16	1200		14.03	10.16	3.87	0.72	2.30	4.51E-10	2.94E-06	0.013		14.74
17	1275		14.03	10.16	3.87	0.72	2.30	4.51E-10	2.95E-06	0.013		14.75
18	1350		14.04	10.16	3.87	0.72	2.30	4.51E-10	2.95E-06	0.013		14.75
19	1425		14.04	10.16	3.87	0.72	2.30	4.51E-10	2.95E-06	0.013		14.75
20	1500		14.04	10.17	3.87	0.72	2.30	4.51E-10	2.95E-06	0.013		14.75
21	1575		14.04	10.17	3.87	0.72	2.30	4.51E-10	2.95E-06	0.013		14.75
22	1650		14.04	10.17	3.87	0.72	2.30	4.51E-10	2.95E-06	0.013		14.75
23	1725		14.04	10.17	3.87	0.72	2.30	4.51E-10	2.95E-06	0.013		14.75
24	1800		14.04	10.17	3.87	0.72	2.30	4.51E-10	2.95E-06	0.013		14.75
25	1875		14.04	10.17	3.87	0.72	2.30	4.51E-10	2.95E-06	0.013		14.76

Table 10. Evaluation of an External Axial Flaw for Fatigue Crack Growth Along Path 2 (Cont'd)

AXIAL FLAW FATIGUE CRACK GROWTH FOR REMAINING TRANSIENTS

Basis: $\Delta a = \Delta N * C_o(\Delta KI)^n$

Transient frequency: 2760 cycles over 40 years

ΔN = 69 cycles/year

Operating Time (yr.)	Cycle	a (in.)	NU1 KI(a)max (ksi√in)	NU2 KI(a)min (ksi√in)	ΔKI (ksi√in)	R	S	C_o	Δa (in.)	r_y	a_e	NU1 KI(a_e)max (ksi√in)
0	0		15.02	8.66	6.35	0.58	2.04	3.99E-10	1.23E-05	0.015		15.91
1	69		15.02	8.66	6.36	0.58	2.04	3.99E-10	1.23E-05	0.015		15.91
2	138		15.02	8.66	6.36	0.58	2.04	3.99E-10	1.23E-05	0.015		15.91
3	207		15.02	8.66	6.36	0.58	2.04	3.99E-10	1.23E-05	0.015		15.91
4	276		15.02	8.66	6.36	0.58	2.04	3.99E-10	1.23E-05	0.015		15.91
5	345		15.02	8.66	6.36	0.58	2.04	3.99E-10	1.23E-05	0.015		15.91
6	414		15.02	8.67	6.36	0.58	2.04	3.99E-10	1.23E-05	0.015		15.92
7	483		15.02	8.67	6.36	0.58	2.04	3.99E-10	1.23E-05	0.015		15.92
8	552		15.03	8.67	6.36	0.58	2.04	3.99E-10	1.23E-05	0.015		15.92
9	621		15.03	8.67	6.36	0.58	2.04	3.99E-10	1.23E-05	0.015		15.92
10	690		15.03	8.67	6.36	0.58	2.04	3.99E-10	1.23E-05	0.015		15.92
11	759		15.03	8.67	6.36	0.58	2.04	3.99E-10	1.23E-05	0.015		15.92
12	828		15.03	8.67	6.36	0.58	2.04	3.99E-10	1.23E-05	0.015		15.92
13	897		15.03	8.67	6.36	0.58	2.04	3.99E-10	1.23E-05	0.015		15.92
14	966		15.03	8.67	6.36	0.58	2.04	3.99E-10	1.24E-05	0.015		15.93
15	1035		15.03	8.67	6.36	0.58	2.04	3.99E-10	1.24E-05	0.015		15.93
16	1104		15.04	8.67	6.36	0.58	2.04	3.99E-10	1.24E-05	0.015		15.93
17	1173		15.04	8.67	6.36	0.58	2.04	3.99E-10	1.24E-05	0.015		15.93
18	1242		15.04	8.67	6.36	0.58	2.04	3.99E-10	1.24E-05	0.015		15.93
19	1311		15.04	8.67	6.37	0.58	2.04	3.99E-10	1.24E-05	0.015		15.93
20	1380		15.04	8.68	6.37	0.58	2.04	3.99E-10	1.24E-05	0.015		15.93
21	1449		15.04	8.68	6.37	0.58	2.04	3.99E-10	1.24E-05	0.015		15.93
22	1518		15.04	8.68	6.37	0.58	2.04	3.99E-10	1.24E-05	0.015		15.94
23	1587		15.04	8.68	6.37	0.58	2.04	3.99E-10	1.24E-05	0.015		15.94
24	1656		15.05	8.68	6.37	0.58	2.04	3.99E-10	1.24E-05	0.015		15.94
25	1725		15.05	8.68	6.37	0.58	2.04	3.99E-10	1.24E-05	0.015		15.94

Table 11. Evaluation of a Continuous Surface Crack for Fatigue Crack Growth Along Path 4

INPUT DATA

Geometry:	Plate thickness,	t =	0.981	in.
Flaw Size:	Flaw depth,	a =	0.100	in.
		a/t =	0.102	
Environment:	Temperature,	T =	600	F
Material Strength:	Yield strength,	σ_{ys} =	27.9	ksi

Table 11. Evaluation of a Continuous Surface Crack for Fatigue Crack Growth Along Path 4 (Cont'd)

PLATE SURFACE FLAW STRESS INTENSITY FACTOR FOR HEATUP AND COOLDOWN STRESSES

Basis: Analysis of Flaws, 1995 ASME Code, Section XI, Appendix A (Ref. 16)

$$KI = [A_0 G_0 + A_1 G_1 + A_2 G_2 + A_3 G_3] \sqrt{(\pi a/Q)}$$

where $Q = 1 + 4.593*(a/l)^{1.65} - q_y$

and $q_y = [(A_0 G_0 + A_1 G_1 + A_2 G_2 + A_3 G_3) / \sigma_{ys}]^2 / 6$

For a/l = 0.0 (continuous flaw)
a/t <= 0.1

Go = 1.1945
G_1 = 0.7732
G_2 = 0.5996
G_3 = 0.5012

Stresses are described by a third order polynomial fit over the flaw depth,

$$S(x) = A_0 + A_1(x/a) + A_2(x/a)^2 + A_3(x/a)^3$$

Radial Stresses:

Wall Position x	Normal/Upset Cond. Stresses [6]	
	SS*	Shutdown
(in.)	(ksi)	(ksi)
0.00000		
0.24535		
0.49070		
0.73604		
0.98139		

* Heatup/Cooldown transient at 6.0 hours (steady state) using stresses for Path 4

Stress Coefficients: a = 0.100 in.

Stress Coeff.	Normal/Upset Loading Conditions	
	NU1	NU2
	(ksi)	(ksi)
A_0		
A_1		
A_2		
A_3		

Table 11. Evaluation of a Continuous Surface Crack for Fatigue Crack Growth Along Path 4 (Cont'd)

PLATE SURFACE FLAW STRESS INTENSITY FACTOR FOR PLANT LOADING AND UNLOADING STRESSES

Basis: Analysis of Flaws, 1995 ASME Code, Section XI, Appendix A (Ref. 16)

$$KI = [A_0 G_0 + A_1 G_1 + A_2 G_2 + A_3 G_3] \sqrt{(\pi a/Q)}$$

where $Q = 1 + 4.593*(a/l)^{1.65} - q_y$

and $q_y = [(A_0 G_0 + A_1 G_1 + A_2 G_2 + A_3 G_3) / \sigma_{ys}]^2 / 6$

For a/l = 0.0 (continuous flaw)
a/t <= 0.1

Go = 1.1945
G_1 = 0.7732
G_2 = 0.5996
G_3 = 0.5012

Stresses are described by a third order polynomial fit over the flaw depth,

$$S(x) = A_0 + A_1(x/a) + A_2(x/a)^2 + A_3(x/a)^3$$

Radial Stresses:

Wall Position x	Normal/Upset Cond. Stresses [6]	
	PU*	PL**
(in.)	(ksi)	(ksi)
0.00000		
0.24535		
0.49070		
0.73604		
0.98139		

* Plant Loading/Unloading transient at 3.333 hours (plant unloading) using stresses for Path 4

** Plant Loading/Unloading transient at 0.333 hours (plant loading) using stresses for Path 4

Stress Coefficients: a = 0.100 in.

Stress Coeff.	Normal/Upset Loading Conditions	
	NU1	NU2
	(ksi)	(ksi)
A_0		
A_1		
A_2		
A_3		

Table 11. Evaluation of a Continuous Surface Crack for Fatigue Crack Growth Along Path 4 (Cont'd)

PLATE SURFACE FLAW STRESS INTENSITY FACTOR FOR REMAINING TRANSIENT STRESSES

Basis: Analysis of Flaws, 1995 ASME Code, Section XI, Appendix A (Ref. 16)

$$KI = [\, A_0\, G_0 + A_1\, G_1 + A_2\, G_2 + A_3\, G_3\,]\ \sqrt{(\pi a/Q)}$$

where $Q = 1 + 4.593^*(a/l)^\wedge 1.65 - q_y$

and $q_y = [\,(A_0\, G_0 + A_1\, G_1 + A_2\, G_2 + A_3\, G_3) / \sigma_{ys}\,]^2 / 6$

For a/l = 0.0 (continuous flaw)
a/t <= 0.1

Go = 1.1945
G_1 = 0.7732
G_2 = 0.5996
G_3 = 0.5012

Stresses are described by a third order polynomial fit over the flaw depth,

$$S(x) = A_0 + A_1(x/a) + A_2(x/a)^2 + A_3(x/a)^3$$

Radial Stresses:

Wall Position x	Normal/Upset Cond. Stresses [6]	
	LL1*	LL2**
(in.)	(ksi)	(ksi)
0.00000		
0.24535		
0.49070		
0.73604		
0.98139		

* Loss of Load transient at 0.00278 hours (max. stress) using stresses for Path 4

** Loss of Load transient at 0.0444 hours (min. stress) using stresses for Path 4

Stress Coefficients: a = 0.100 in.

Stress Coeff.	Normal/Upset Loading Conditions	
	NU1	NU2
	(ksi)	(ksi)
A_0		
A_1		
A_2		
A_3		

Table 11. Evaluation of a Continuous Surface Crack for Fatigue Crack Growth Along Path 4 (Cont'd)

CONTINUOUS SURFACE FLAW FATIGUE CRACK GROWTH FOR HEATUP AND COOLDOWN TRANSIENT

Basis: $\Delta a = \Delta N * C_o(\Delta KI)^n$

Transient frequency: 200 cycles over 40 years

$\Delta N =$ 5 cycles/year

Operating Time (yr.)	Cycle	a (in.)	Q	NU1 KI(a)max (ksi√in)	NU2 KI(a)min (ksi√in)	ΔKI (ksi√in)	R	S	C_o	Δa (in.)	q_y	$Q(a_e)$	$KI(a_e)$max (ksi√in)
0	0	0.10000	1.000	17.32	0.00	17.32	0.00	1.00	1.96E-10	1.20E-05	0.204	0.796	19.42
1	5		1.000	17.32	0.00	17.32	0.00	1.00	1.96E-10	1.20E-05	0.204	0.796	19.42
2	10		1.000	17.33	0.00	17.33	0.00	1.00	1.96E-10	1.20E-05	0.204	0.796	19.43
3	15		1.000	17.33	0.00	17.33	0.00	1.00	1.96E-10	1.20E-05	0.204	0.796	19.43
4	20		1.000	17.33	0.00	17.33	0.00	1.00	1.96E-10	1.20E-05	0.204	0.796	19.43
5	25		1.000	17.34	0.00	17.34	0.00	1.00	1.96E-10	1.20E-05	0.204	0.796	19.44
6	30		1.000	17.34	0.00	17.34	0.00	1.00	1.96E-10	1.20E-05	0.204	0.796	19.44
7	35		1.000	17.34	0.00	17.34	0.00	1.00	1.96E-10	1.20E-05	0.204	0.796	19.44
8	40		1.000	17.34	0.00	17.34	0.00	1.00	1.96E-10	1.20E-05	0.204	0.796	19.45
9	45		1.000	17.35	0.00	17.35	0.00	1.00	1.96E-10	1.20E-05	0.204	0.796	19.45
10	50		1.000	17.35	0.00	17.35	0.00	1.00	1.96E-10	1.20E-05	0.204	0.796	19.45
11	55		1.000	17.35	0.00	17.35	0.00	1.00	1.96E-10	1.20E-05	0.204	0.796	19.46
12	60		1.000	17.36	0.00	17.36	0.00	1.00	1.96E-10	1.20E-05	0.204	0.796	19.46
13	65		1.000	17.36	0.00	17.36	0.00	1.00	1.96E-10	1.21E-05	0.204	0.796	19.46
14	70		1.000	17.36	0.00	17.36	0.00	1.00	1.96E-10	1.21E-05	0.204	0.796	19.47
15	75		1.000	17.37	0.00	17.37	0.00	1.00	1.96E-10	1.21E-05	0.204	0.796	19.47
16	80		1.000	17.37	0.00	17.37	0.00	1.00	1.96E-10	1.21E-05	0.204	0.796	19.47
17	85		1.000	17.37	0.00	17.37	0.00	1.00	1.96E-10	1.21E-05	0.204	0.796	19.48
18	90		1.000	17.38	0.00	17.38	0.00	1.00	1.96E-10	1.21E-05	0.204	0.796	19.48
19	95		1.000	17.38	0.00	17.38	0.00	1.00	1.96E-10	1.21E-05	0.204	0.796	19.48
20	100		1.000	17.38	0.00	17.38	0.00	1.00	1.96E-10	1.21E-05	0.204	0.796	19.49
21	105		1.000	17.38	0.00	17.38	0.00	1.00	1.96E-10	1.21E-05	0.204	0.796	19.49
22	110		1.000	17.39	0.00	17.39	0.00	1.00	1.96E-10	1.21E-05	0.204	0.796	19.49
23	115		1.000	17.39	0.00	17.39	0.00	1.00	1.96E-10	1.21E-05	0.204	0.796	19.50
24	120		1.000	17.39	0.00	17.39	0.00	1.00	1.96E-10	1.21E-05	0.204	0.796	19.50
25	125		1.000	17.40	0.00	17.40	0.00	1.00	1.96E-10	1.21E-05	0.204	0.796	19.50

Table 11. Evaluation of a Continuous Surface Crack for Fatigue Crack Growth Along Path 4 (Cont'd)

CONTINUOUS SURFACE FLAW FATIGUE CRACK GROWTH FOR PLANT LOADING AND UNLOADING TRANSIENT

Basis: $\Delta a = \Delta N * C_o(\Delta KI)^n$

Transient frequency: 3000 cycles over 40 years

$\Delta N =$ 75 cycles/year

Operating Time (yr.)	Cycle	a (in.)	Q	NU1 KI(a)max (ksi√in)	NU2 KI(a)min (ksi√in)	ΔKI (ksi√in)	R	S	C_o	Δa (in.)	q_y	$Q(a_e)$	$KI(a_e)max$ (ksi√in)
0	0		1.000	18.25	12.08	6.17	0.66	2.19	4.29E-10	1.30E-05	0.227	0.773	20.76
1	75		1.000	18.25	12.09	6.17	0.66	2.19	4.29E-10	1.30E-05	0.227	0.773	20.76
2	150		1.000	18.26	12.09	6.17	0.66	2.19	4.29E-10	1.30E-05	0.227	0.773	20.77
3	225		1.000	18.26	12.09	6.17	0.66	2.19	4.29E-10	1.31E-05	0.227	0.773	20.77
4	300		1.000	18.26	12.09	6.17	0.66	2.19	4.29E-10	1.31E-05	0.227	0.773	20.77
5	375		1.000	18.27	12.09	6.17	0.66	2.19	4.29E-10	1.31E-05	0.227	0.773	20.78
6	450		1.000	18.27	12.10	6.17	0.66	2.19	4.29E-10	1.31E-05	0.227	0.773	20.78
7	525		1.000	18.27	12.10	6.18	0.66	2.19	4.29E-10	1.31E-05	0.227	0.773	20.78
8	600		1.000	18.28	12.10	6.18	0.66	2.19	4.29E-10	1.31E-05	0.227	0.773	20.79
9	675		1.000	18.28	12.10	6.18	0.66	2.19	4.29E-10	1.31E-05	0.227	0.773	20.79
10	750		1.000	18.28	12.10	6.18	0.66	2.19	4.29E-10	1.31E-05	0.227	0.773	20.80
11	825		1.000	18.29	12.11	6.18	0.66	2.19	4.29E-10	1.31E-05	0.227	0.773	20.80
12	900		1.000	18.29	12.11	6.18	0.66	2.19	4.29E-10	1.31E-05	0.227	0.773	20.80
13	975		1.000	18.29	12.11	6.18	0.66	2.19	4.29E-10	1.31E-05	0.227	0.773	20.81
14	1050		1.000	18.30	12.11	6.18	0.66	2.19	4.29E-10	1.31E-05	0.227	0.773	20.81
15	1125		1.000	18.30	12.12	6.18	0.66	2.19	4.29E-10	1.31E-05	0.227	0.773	20.81
16	1200		1.000	18.30	12.12	6.19	0.66	2.19	4.29E-10	1.32E-05	0.227	0.773	20.82
17	1275		1.000	18.31	12.12	6.19	0.66	2.19	4.29E-10	1.32E-05	0.227	0.773	20.82
18	1350		1.000	18.31	12.12	6.19	0.66	2.19	4.29E-10	1.32E-05	0.227	0.773	20.83
19	1425		1.000	18.31	12.12	6.19	0.66	2.19	4.29E-10	1.32E-05	0.227	0.773	20.83
20	1500		1.000	18.32	12.13	6.19	0.66	2.19	4.29E-10	1.32E-05	0.227	0.773	20.83
21	1575		1.000	18.32	12.13	6.19	0.66	2.19	4.29E-10	1.32E-05	0.227	0.773	20.84
22	1650		1.000	18.32	12.13	6.19	0.66	2.19	4.29E-10	1.32E-05	0.227	0.773	20.84
23	1725		1.000	18.33	12.13	6.19	0.66	2.19	4.29E-10	1.32E-05	0.227	0.773	20.84
24	1800		1.000	18.33	12.13	6.19	0.66	2.19	4.29E-10	1.32E-05	0.227	0.773	20.85
25	1875		1.000	18.33	12.14	6.20	0.66	2.19	4.29E-10	1.32E-05	0.227	0.773	20.85

Table 11. Evaluation of a Continuous Surface Crack for Fatigue Crack Growth Along Path 4 (Cont'd)

CONTINUOUS SURFACE FLAW FATIGUE CRACK GROWTH FOR REMAINING TRANSIENTS

Basis: $\Delta a = \Delta N * C_o(\Delta KI)^n$

Transient frequency: 2760 cycles over 40 years

ΔN = 69 cycles/year

Operating Time (yr.)	Cycle	a (in.)	Q	NU1 KI(a)max (ksi√in)	NU2 KI(a)min (ksi√in)	ΔKI (ksi√in)	R	S	C_o	Δa (in.)	q_y	$Q(a_e)$	$KI(a_e)max$ (ksi√in)
0	0		1.000	18.17	12.31	5.87	0.68	2.22	4.34E-10	1.03E-05	0.225	0.775	20.64
1	69		1.000	18.17	12.31	5.87	0.68	2.22	4.34E-10	1.03E-05	0.225	0.775	20.64
2	138		1.000	18.18	12.31	5.87	0.68	2.22	4.34E-10	1.03E-05	0.225	0.775	20.65
3	207		1.000	18.18	12.31	5.87	0.68	2.22	4.34E-10	1.03E-05	0.225	0.775	20.65
4	276		1.000	18.18	12.31	5.87	0.68	2.22	4.34E-10	1.03E-05	0.225	0.775	20.66
5	345		1.000	18.19	12.32	5.87	0.68	2.22	4.34E-10	1.03E-05	0.225	0.775	20.66
6	414		1.000	18.19	12.32	5.87	0.68	2.22	4.34E-10	1.03E-05	0.225	0.775	20.66
7	483		1.000	18.19	12.32	5.87	0.68	2.22	4.34E-10	1.03E-05	0.225	0.775	20.67
8	552		1.000	18.20	12.32	5.87	0.68	2.22	4.34E-10	1.03E-05	0.225	0.775	20.67
9	621		1.000	18.20	12.33	5.87	0.68	2.22	4.34E-10	1.03E-05	0.225	0.775	20.67
10	690		1.000	18.20	12.33	5.88	0.68	2.22	4.34E-10	1.03E-05	0.225	0.775	20.68
11	759		1.000	18.21	12.33	5.88	0.68	2.22	4.34E-10	1.03E-05	0.225	0.775	20.68
12	828		1.000	18.21	12.33	5.88	0.68	2.22	4.34E-10	1.04E-05	0.225	0.775	20.69
13	897		1.000	18.21	12.33	5.88	0.68	2.22	4.34E-10	1.04E-05	0.225	0.775	20.69
14	966		1.000	18.22	12.34	5.88	0.68	2.22	4.34E-10	1.04E-05	0.225	0.775	20.69
15	1035		1.000	18.22	12.34	5.88	0.68	2.22	4.34E-10	1.04E-05	0.225	0.775	20.70
16	1104		1.000	18.22	12.34	5.88	0.68	2.22	4.34E-10	1.04E-05	0.225	0.775	20.70
17	1173		1.000	18.23	12.34	5.88	0.68	2.22	4.34E-10	1.04E-05	0.225	0.775	20.70
18	1242		1.000	18.23	12.35	5.88	0.68	2.22	4.34E-10	1.04E-05	0.225	0.775	20.71
19	1311		1.000	18.23	12.35	5.88	0.68	2.22	4.34E-10	1.04E-05	0.225	0.775	20.71
20	1380		1.000	18.24	12.35	5.89	0.68	2.22	4.34E-10	1.04E-05	0.225	0.775	20.71
21	1449		1.000	18.24	12.35	5.89	0.68	2.22	4.34E-10	1.04E-05	0.225	0.775	20.72
22	1518		1.000	18.24	12.35	5.89	0.68	2.22	4.34E-10	1.04E-05	0.225	0.775	20.72
23	1587		1.000	18.25	12.36	5.89	0.68	2.22	4.34E-10	1.04E-05	0.225	0.775	20.73
24	1656		1.000	18.25	12.36	5.89	0.68	2.22	4.34E-10	1.04E-05	0.225	0.775	20.73
25	1725		1.000	18.25	12.36	5.89	0.68	2.22	4.34E-10	1.04E-05	0.225	0.775	20.73

9.0 SUMMARY OF RESULTS

The flaw evaluation results for 25 years of fatigue crack growth are as follows.

9.1 Propagation of a Continuous External Circumferential Flaw Along Path 2

a) Fatigue crack growth analysis:

Initial flaw size,	a_i = 0.100 in.
Final flaw size,	a_f = [ ] in.
Stress intensity factor at final flaw size,	$K_I(a_{ef})$ = 17.9 ksi√in
Fracture toughness	K_{Ia} = 200 ksi√in
Fracture toughness margin,	K_{Ia} / K_I = 11.2 > √10

b) Limit load analysis:

Limit load,	P_O = [ ] lbs
Bounding axial tube load,	P(appl) = [ ] lbs
Limit load margin,	P_O / P(appl) = 8.47 > 3.0

9.2 Fatigue Crack Growth of a Semi-Circular External Axial Flaw Along Path 2

Initial flaw size,	a_i = 0.100 in.
Final flaw size,	a_f = [ ] in.
Stress intensity factor at final flaw size,	$K_I(a_{ef})$ = 15.9 ksi√in
Fracture toughness	K_{Ia} = 200 ksi√in
Fracture toughness margin,	K_{Ia} / K_I = 12.6 > √10

9.3 Fatigue Crack Growth of a Continuous Cylindrical Flaw Along Path 4

Initial flaw size,	a_i = 0.100 in.
Final flaw size,	a_f = [ ] in.
Stress intensity factor at final flaw size,	$K_I(a_{ef})$ = 20.9 ksi√in
Fracture toughness	K_{Ia} = 200 ksi√in
Fracture toughness margin,	K_{Ia} / K_I = 9.57 > √10

10.0 CONCLUSION

The results of the analysis demonstrate that the 0.10 inch weld anomaly is acceptable for a 25 year design life of the CRDM ID temper bead weld repair. Significant fracture toughness margins have been demonstrated for both of the flaw propagation paths considered in the analysis. The minimum fracture toughness margins for flaw propagation Paths 2 and 4 have been shown to be 11.2 and 9.57, respectively, as compared to the required margin of $\sqrt{10}$ for normal and upset operating conditions per Section XI, IWB-3612 (Reference 3). Fatigue crack growth is minimal. The maximum final flaw size is [ ] inch (considering both flaw propagation paths). A limit load analysis was also performed considering the ductile Alloy 600/Alloy 690 materials along flaw propagation Path 2. The analysis showed limit load margin of 8.47 for normal and upset operating conditions, as compared to the required margin of 3.0 per Section XI, IWB-3642 (Reference 3).

11.0 REFERENCES

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FRAMATOME ANP

CALCULATION SUMMARY SHEET (CSS)

Document Identifier 32 - 5019396 - 02

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

PREPARED BY:

NAME D.E. KILLIAN

SIGNATURE

TITLE ADVISORY ENGR. DATE 7/25/03

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PURPOSE AND SUMMARY OF RESULTS:

Revision 2: 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
2	All	Revision 2 is a non-proprietary version of Revision 0 that includes more information than Revision 1.	7/03

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.

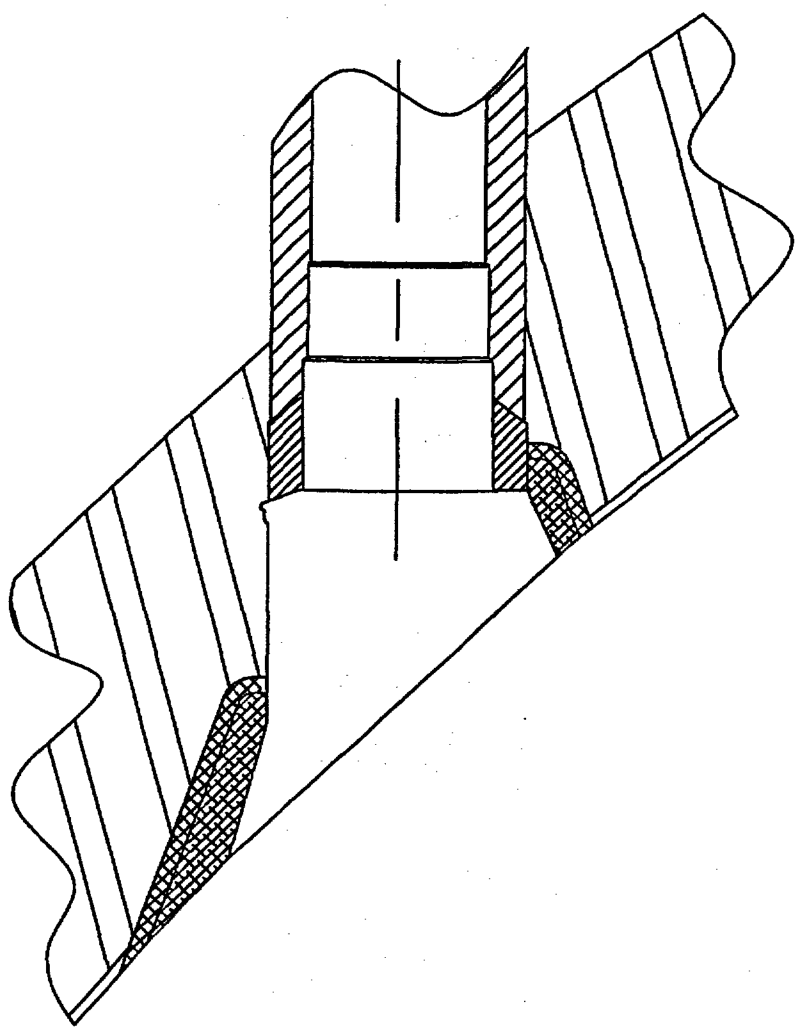

Figure 1. ID Temper Bead Weld Repair

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.

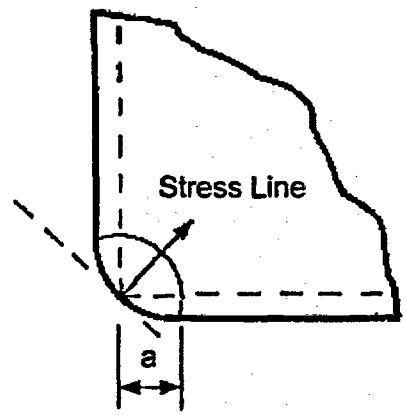

Figure 2. Corner Flaw Model

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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(for legibility concerns)

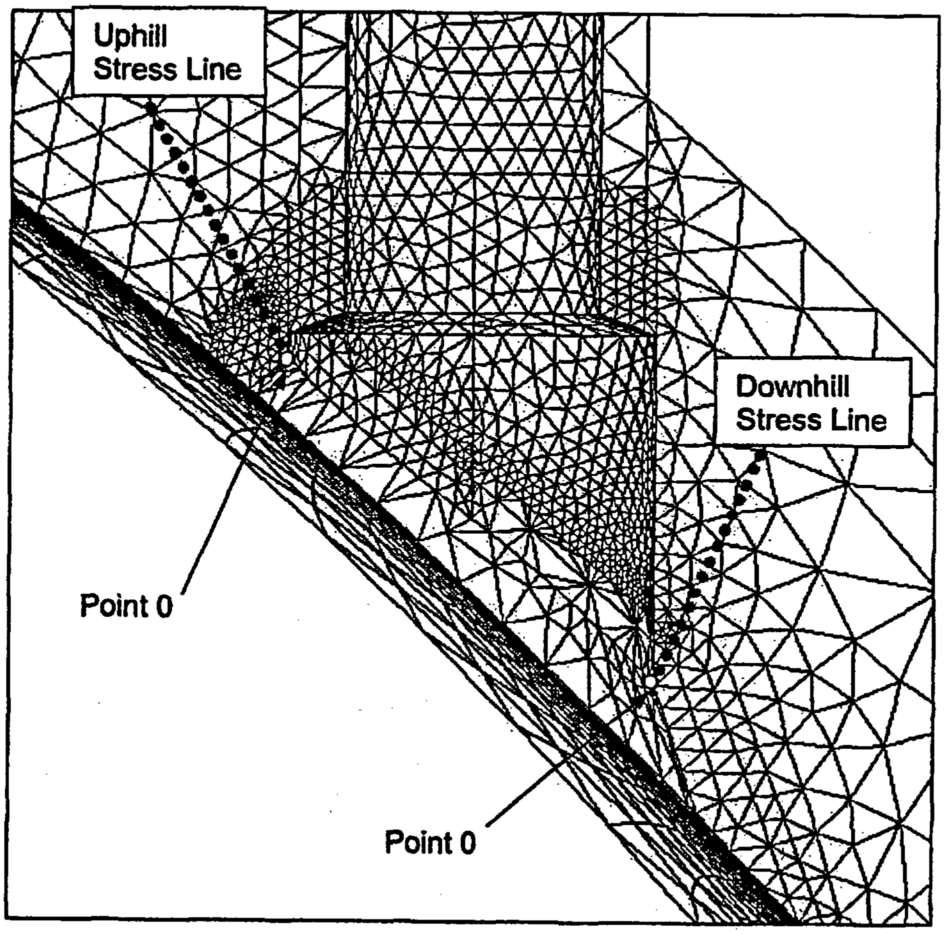


Figure 3. Orientation of Stress Lines

3.0 Material Properties

The portion of the reactor vessel head that contains the CRDM nozzles is fabricated from SA-302 Grade B [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 SA-302 Grade B 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

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

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$\sqrt{\text{in}}$, and T and RT_{NDT} are in °F. In the present flaw evaluations, K_{Ia} is limited to a maximum value of 200 ksi$\sqrt{\text{in}}$ (upper-shelf fracture toughness). Using the above equation with an RT_{NDT} of 60 °F, K_{Ia} equals 200 ksi$\sqrt{\text{in}}$ 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√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)

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

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

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

$\Delta K_I \geq 17.74$,

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

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

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

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

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

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

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

$\Delta K_I \geq 12.04$,

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

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.

Irwin Plasticity Correction

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.)	$\Delta S^{(1)}$ (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).

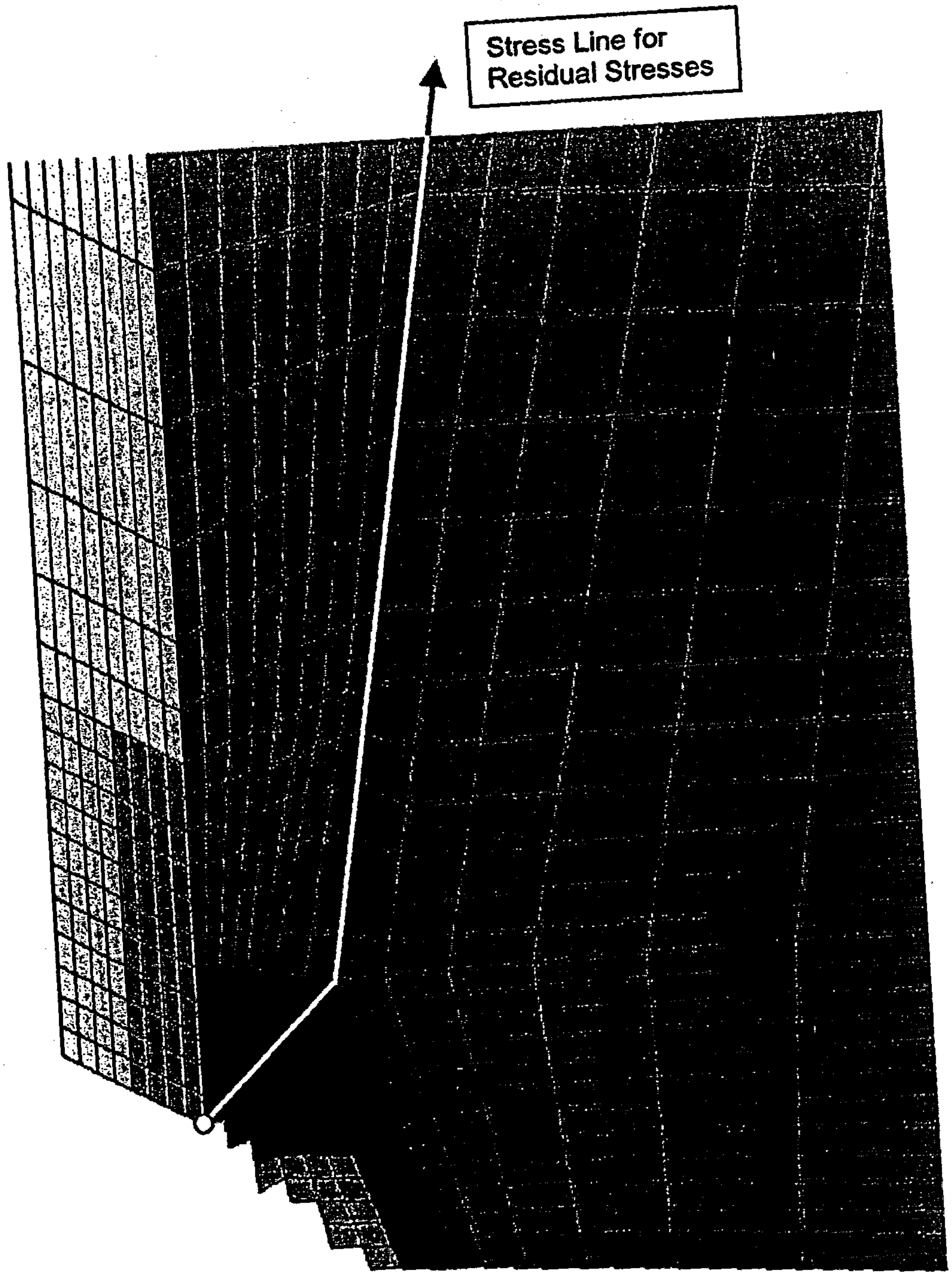
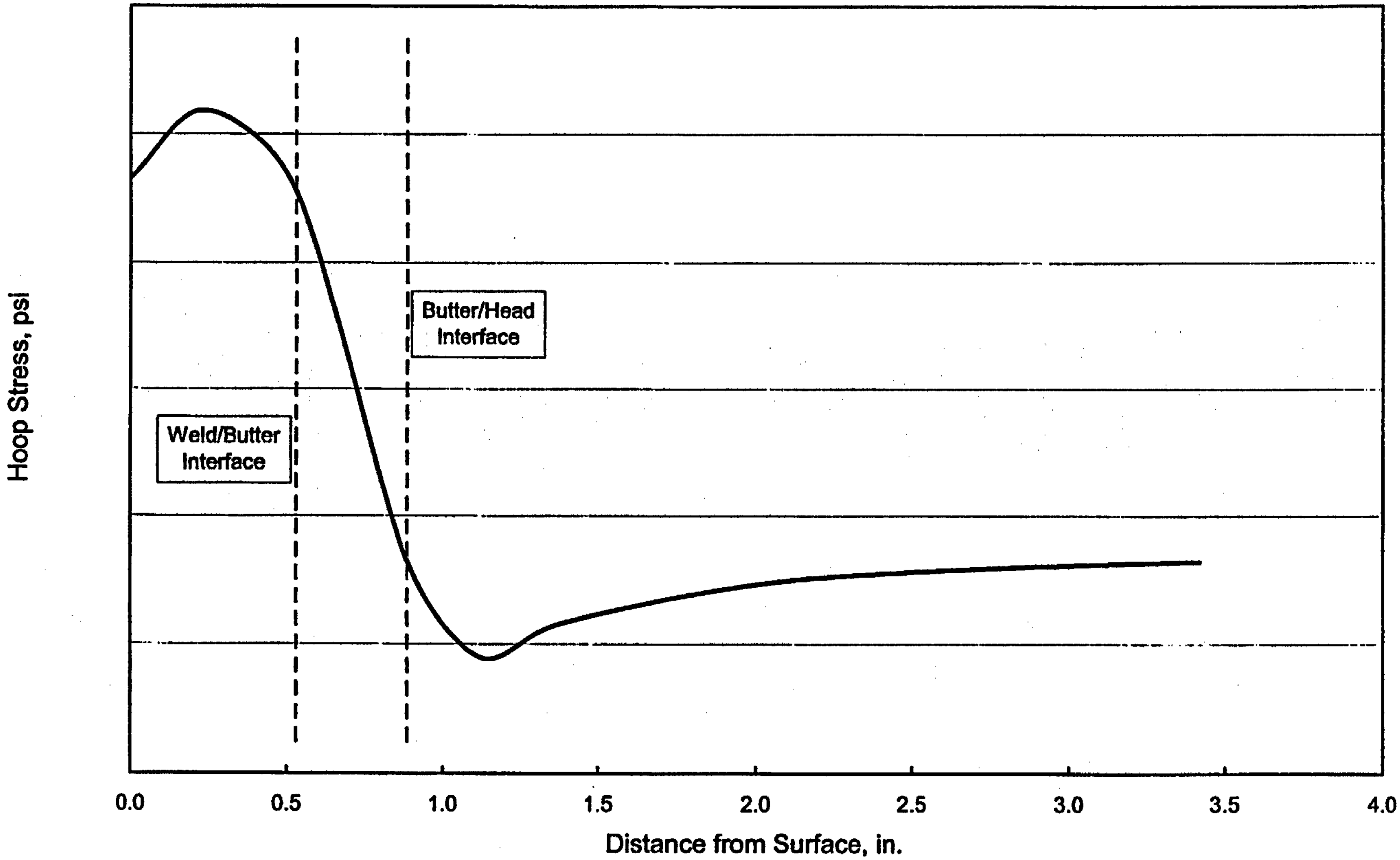


Figure 4. Weld Geometry After Chamfer

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

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

Kla is limited to the upper shelf toughness.

Applied Loads:

	Loading Conditions	
	PU*	PL**
	Temperature (F)	
	547	612
	Pressure, p (ksi)	
	Kla (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)	
	Kla (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		

* 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

$\Delta N =$ 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 = KIa / KI(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

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

Kla is limited to the upper shelf toughness.

Applied Loads:

	Loading Conditions	
	50SR1*	50SR2**
	Temperature (F)	
	548	590
	Pressure, p (ksi)	
	Kla (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
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)	
	Kla (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		

* 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 (ksi)	RT2 (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

$\Delta N =$ 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 = KIa / KI(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			
KI(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

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

Kla is limited to the upper shelf toughness.

Applied Loads:

	Loading Conditions	
	LF1*	LF2**
	Temperature (F)	
	528	612
	Pressure, p (ksi)	
	Kla (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 Margin = KIa / $KI(a_e)$
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)	
	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 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
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.

AFFIDAVIT

COMMONWEALTH OF VIRGINIA)
) ss.
CITY OF LYNCHBURG)

1. My name is James F. Mallay. I am Director, Regulatory Affairs, for Framatome ANP ("FANP"), and as such I am authorized to execute this Affidavit.

2. I am familiar with the criteria applied by FANP to determine whether certain FANP information is proprietary. I am familiar with the policies established by FANP to ensure the proper application of these criteria.

3. I am familiar with the information contained in two calculation summary sheets (32-5019396-02 and 32-5019398-02) describing flaw evaluations on CRDM nozzles for Point Beach, Unit 1. These two documents are being provided to the NRC by Nuclear Management Company in response to a letter from the NRC of April 10, 2003. These two calculation summary sheets are referred to herein as "Documents." Information contained in these Documents has been classified by FANP as proprietary in accordance with the policies established by FANP for the control and protection of proprietary and confidential information.

4. These Documents contain information of a proprietary and confidential nature and is of the type customarily held in confidence by FANP and not made available to the public. Based on my experience, I am aware that other companies regard information of the kind contained in these Documents as proprietary and confidential.

5. These Documents have been made available to the U.S. Nuclear Regulatory Commission in confidence with the request that the information contained in these Documents be withheld from public disclosure.

6. The following criteria are customarily applied by FANP to determine whether information should be classified as proprietary:

(a) The information reveals details of FANP's research and development plans and programs or their results.

(b) Use of the information by a competitor would permit the competitor to significantly reduce its expenditures, in time or resources, to design, produce, or market a similar product or service.

(c) The information includes test data or analytical techniques concerning a process, methodology, or component, the application of which results in a competitive advantage for FANP.

(d) The information reveals certain distinguishing aspects of a process, methodology, or component, the exclusive use of which provides a competitive advantage for FANP in product optimization or marketability.

(e) The information is vital to a competitive advantage held by FANP, would be helpful to competitors to FANP, and would likely cause substantial harm to the competitive position of FANP.

7. In accordance with FANP's policies governing the protection and control of information, proprietary information contained in these Documents has been made available, on a limited basis, to others outside FANP only as required and under suitable agreement providing for nondisclosure and limited use of the information.

8. FANP policy requires that proprietary information be kept in a secured file or area and distributed on a need-to-know basis.

9. The foregoing statements are true and correct to the best of my knowledge, information, and belief.

SUBSCRIBED before me this 30th

day of July, 2003.

Ella F. Carr-Payne
NOTARY PUBLIC, STATE OF VIRGINIA
MY COMMISSION EXPIRES: 8/31/05

ELLA F. CARR-PAYNE
Notary Public
Commonwealth of Virginia
My Commission Exps. Aug. 31, 2005