TVA TENNESSEE VALLEY AUTHORITY

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October 4, 2021

ATTN: Document Control Desk
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555-0001

Browns Ferry Nuclear Plant, Unit 2
Renewed Facility Operating License No. DPR-52
NRC Docket No. 50-260

Subject: **Submittal of Browns Ferry Unit 2 Reactor Pressure Vessel Vertical Weld Flaw Evaluation**

Reference: Letter from TVA to NRC, "American Society of Mechanical Engineers, Section XI, Fifth 10 Year Inspection Interval, Inservice Inspection, System Pressure Test, Containment Inspection, and Repair and Replacement Programs, Owner's Activity Report for Browns Ferry Nuclear Plant, Unit 2, Cycle 21 Operation," dated July 21, 2021 (ML21202A242).

The Tennessee Valley Authority (TVA) previously submitted Browns Ferry Nuclear Plant (BFN), American Society of Mechanical Engineers (ASME), Section XI, Owner's Activity Report for BFN, Unit 2, Cycle 21 Operation. This report described an analytical flaw evaluation on the V-3-A weld. Per ASME Section XI, BFN accepted this flaw for continued service without repair/replacement activities, based upon an evaluation performed by Structural Integrity Associates, Inc. TVA is submitting a copy of the evaluation required by ASME Section XI, Article IWB-3132.3, to the NRC for review, in accordance with ASME Section XI, Article IWB-3134(b).

There are no new regulatory commitments contained in this letter. Should you have any questions concerning this submittal, please contact C. L. Vaughn, Site Licensing Manager, at (256) 729-2636.

Respectfully,

Matthew Rasmussen
Site Vice President

Enclosure: Browns Ferry Unit 2 Reactor Pressure Vessel Vertical Weld Flaw Evaluation

cc (Enclosure): NRC Regional Administrator – Region II
NRC Senior Resident Inspector – Browns Ferry Nuclear Plant
NRC Project Manager – Browns Ferry Nuclear Plant

Enclosure

Tennessee Valley Authority

Browns Ferry Nuclear Plant
Unit 2

Browns Ferry Unit 2 Reactor Pressure Vessel Vertical Weld Flaw Evaluation

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See Enclosed

File No.: **2100264.301**

Project No.: **2100264**

Quality Program Type: ☒ Nuclear ☐ Commercial

CALCULATION PACKAGE

PROJECT NAME:
RPV Vertical Weld Flaw Evaluation for BFN

CONTRACT NO.:
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CLIENT:
Tennessee Valley Authority

PLANT:
Browns Ferry Nuclear Plant Unit 2

CALCULATION TITLE:
Browns Ferry Unit 2 Reactor Pressure Vessel Vertical Weld Flaw Evaluation

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1	1 - 2 7 - 12, 14 16 - 17 19 - 21 B2 - B7	Revised the material fracture toughness upper-shelf limit to 220 ksi$\sqrt{in}$. Revised Appendix B: The start-up transient is used as bounding thermal transient. Revised Section 7.0 and Section 8.0: Included the proximity of the flaw to the ID as well as the OD	Moses Taylor 07/08/2021	Garivalde Dominguez 07/08/2021 Mohammed Uddin 07/08/2021 Richard Bax 07/08/2021 Rohan Dutta 07/08/2021

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1.0 INTRODUCTION

During ultrasonic examination of the Browns Ferry Nuclear (BFN) Unit 2 reactor pressure vessel (RPV), an indication in a vertical weld was identified that exceeds the acceptance standards of ASME Code, Section XI, IWB-3500 [1]. Therefore, a flaw evaluation per the requirements of IWB-3600 is required.

This calculation provides fracture mechanics analysis of an RPV vertical weld axial flaw configuration to assess the stability and potential for flaw growth.

2.0 METHODOLOGY

The flaw evaluation in this calculation applies fracture mechanics solutions for bounding flaw geometry and loading conditions and uses linear elastic fracture mechanics methods (LEFM) consistent with the requirements of ASME Boiler and Pressure Vessel Code, Section XI, IWB-3600 and Nonmandatory Appendix A [1]. The Structural Integrity Associates fracture mechanics software **pc-CRACK 5.0** [2] is used for these calculations.

Note: In the present calculation, conventional US units are used (length = inches, pressure = kilo-pounds force/inch^2 (i.e., ksi), stress intensity factor and toughness = kilo-pound force/in^2 * √(inch) (i.e., ksi√in)).

3.0 DESIGN INPUTS

1. The indication is reported as being subsurface, separated from the vessel base metal/clad interface by 2.2 inches [3]. The cross-flaw depth dimension in the vessel radial direction ($2a$) is 3.2 inches [3]. The flaw is in the vertical weld V-3-A at 107° azimuth, or 72 to 74.25 inches above the circumferential weld C-2-3 [3, 4]. Details of the geometric parameters of the subsurface flaw are summarized in Figure 1.
2. The plate material of the RPV is SA-302 Grade B [5].
3. From Reference [6, Table Y-1], the yield strength, S_y for SA-302 Grade B, is 42.1 ksi at 600°F, which bounds the plant operating temperature.
4. The vessel has an inside radius (centerline to base metal) of 125.6875 inches [5]. At the flaw location, the vessel wall thickness is 6.4 inches [3].

4.0 ASSUMPTIONS

1. From Reference [5, page 109], the vertical weld has been repaired on the outside diameter. This information provides evidence that weld V-3-A weld is subjected to weld residual stress (WRS). Due to limited information on the weld repair, a uniform 8 ksi membrane stress is assumed as the WRS distribution across the vertical weld. This is the maximum value from the WRS profile provided in EPRI Technical Report 100251 [6, Figure 3-24].
2. From Reference [8], the vertical weld type is an Electroslag Weld (ESW). To calculate the fracture toughness for crack initiation (K_{Ic}), the materials information for ESW is used [9, Table 2.1-2b] with an assumed peak fluence level of 1×10^{17} n/cm^2 which is determined from Reference [10, Table 4]. The adjusted reference temperature is determined using the embrittlement prediction method in Reg. Guide 1.99, Rev. 2 [11].

5.0 CALCULATIONS

5.1 Flaw Characterization Requirements

The geometry for the indication is shown in Figure 1, based on Reference [3]. The indication is assumed as a planar flaw. For the subsurface criteria of ASME Code, Section XI, the rules of IWA-3320 and Figure IWA-3320-1 are used [1]. IWA-3320 states that flaws may be treated as subsurface if $S \geq 0.4a$, where "S" is the separation distance to the nearest surface (neglecting any cladding) and "a" is half of the flaw depth in the radial direction. From Figure 1, S is 1.0 inch while a is 1.6 inches. The criterion is applied for the indication as follows:

$$(S = 1.0 \text{ inch}) \geq (0.4a = 0.4 \times 1.6 \text{ inch} = 0.64 \text{ inch})$$

Therefore, the indication is treated as a subsurface flaw.

5.2 Material Fracture Toughness

In order to evaluate acceptability through the license renewal period, the projected 48 EFPY fluence information was established to determine fracture toughness for vertical weld V-3-A in the BFN, Unit 2. The fluence in the intermediate shell course 3, where vertical weld V-3-A is located, is confirmed to be below the threshold of 1×10^{17} n/cm^2 for the reactor vessel materials [10] at 48 EFPY. This would suggest that the effects of embrittlement need not be considered in determining the fracture toughness. However, for conservatism, the effects of embrittlement on changes in toughness properties were therefore considered using the embrittlement prediction methods for the threshold fluence level.

The calculated toughness for 48 EFPY is determined using the ESW material information are obtained from Reference [9, Table 2.1-2.b], with an assumed maximum fluence of $1\text{x}10^{17}$ n/cm^2 [10].

The fluence attenuation formula from US NRC Regulatory Guide 1.99, Revision 2, can be used to determine fluence at a depth, x, through the thickness of the vessel [11]. The formula is:

$$f(x) = f_{surf} \times \exp(-0.24x)$$

where f_{surf} (10^{19} n/cm^2, E > 1 MeV) is the calculated value of the neutron fluence at the inside diameter (ID) of the vessel, and x (in inches) is the depth into the vessel measured from the ID surface.

The minimum inside depth of the tip is 2.2 inches from the clad-base metal interface. For a depth of 2.2 inches from the vessel ID, the maximum 48 EFPY fluence at the crack tip is:

$$f(2.2 \text{ inches}) = (1 \times 10^{17})\ [10] \times \exp(-0.24\times2.2) = 5.9\times10^{16} \text{ n/cm}^2$$

Table 1 shows that the chemistry factor, CF, is 141°F and the initial material reference temperature, $RT_{NDT,}$ is 23.1°F.

The adjusted reference temperature (ART) in units of °F is given by [11]:

$$ART = \text{Initial } RT_{NDT} + \Delta RT_{NDT} + \text{Margin}$$

where:

$$\Delta RT_{NDT} = (CF) \times f^{(0.28 - 0.1 \log f)}$$

Fluence, f, is in units of 10^{19} n/cm^2. The standard Margin Term is 28°F for welds, except that the Margin Term need not exceed the value of ΔRT_{NDT} [11].

Thus, the maximum ART value at 48 EFPY can be determined as follows:

$$ART = 23.1 + 141 \times 0.0059^{(0.28 - 0.1 \log 0.0059)} + Margin = 23.1 + 10.7 + 10.7$$

$$ART = 44.4°F$$

The fracture toughness of the weld material in vertical weld V-3-A is determined by the reference fracture toughness, K_{Ic} curve [1, Article A-4200]. This is the lower bound initiation toughness as a function of material temperature and material reference temperature ($T - RT_{NDT}$). To account for effects of irradiation on the material fracture toughness in evaluating a flaw in the vessel in regions subjected to fast neutron fluence, the material reference temperature, RT_{NDT}, is equal to the ART value.

The material toughness, K_{Ic}, as a function of ($T - RT_{NDT}$) is given from the following relation from Reference [Figure 1, Article A-4200]:

$$K_{Ic} = 33.2 + 20.734 \times \exp [\, 0.02 \times (T - RT_{NDT})] \quad \text{in units of ksi}\sqrt{\text{in}}$$

The results for toughness, K_{Ic}, for 48 EFPY as a function of temperature, T, are shown in Figure 2 and are tabulated in Table 2.

From inspection of Table 2 and Figure 2, for all temperatures above 154.25°F, the material exhibits upper shelf behavior. Consequently, in Figure 2, the toughness curves from ASME Code, Section XI, Article A-4200(b) [1] are truncated with an (assumed) upper shelf cutoff limit of 220 ksi$\sqrt{\text{in}}$. Per Reference [20], there are no plant evolutions where the vessel temperature is allowed to be below 200.6°F up to normal operating pressure.

Using the structural factors (i.e., margin) imposed by IWB-3612 [1] for acceptance criteria based on applied stress intensity factor, the allowable fracture toughness for normal (Levels A and B) conditions is $220/\sqrt{10}$ = 69.57 ksi$\sqrt{\text{in}}$. For emergency and faulted conditions (Levels C and D), the allowable fracture toughness is $220/\sqrt{2}$ = 155.56 ksi$\sqrt{\text{in}}$. The allowable fracture toughness for Service Levels C and D is at least two times greater than Service Levels A and B and therefore it would take operating loads twice as much for Service Levels C and D to be controlling. As will be shown below, the most dominant load is pressure and Service Level D operating pressure is only marginally above that for normal operating and upset conditions. Therefore, Service Level A/B is controlling.

5.3 Stress Calculations

In the following sections, pressure, thermal, and weld residual stresses are calculated normal to the subsurface flaw, i.e., in the hoop direction.

5.3.1 Hoop Stress Due to Pressure Load

The observed flaw is in the RPV shell in a vertical weld. It is therefore subject to the hoop stress due to the internal pressure in this cylindrical location. The hoop stress is calculated as:

$\sigma_{Hoop} = PR_m/t = 21{,}024$ psi = 21 ksi

where:

P = Maximum pressure	= 1044 psig [12]
t = thickness	= 6.4 inches [3]
R_m = Mean radius	= 128.8875 inches ($D_i/2 - t/2$), D_i = 251.375 inches [5]

The hoop stress is treated as a membrane stress through the vessel wall.

5.3.2 Hoop Stress Due to Thermal Transient

The thermal stress at the flaw location due to limiting transient was determined by finite element analysis. A linear stress distribution (membrane plus bending) is used for the thermal transient stress: $\sigma = -0.6393x + 5.6602$, where x is the distance from the outside diameter to inside diameter. The details of the thermal stress analysis and results are discussed in Appendix B.

5.3.3 Weld Residual Stress

Based on EPRI Technical Report 100251 [7, Figure 3-24], the maximum weld residual stress in the base metal of the RPV is assumed to be 8 ksi tensile. Note that near the center of the RPV wall, the residual stress is compressive but a constant tensile membrane stress of 8 ksi is used.

5.4 Fracture Mechanics Analysis

The Structural Integrity Associates proprietary software **pc-CRACK** [2] is used to perform flaw stability and fatigue crack growth calculations. The flaw is analyzed as a sub-surface elliptical crack in a flat plate, as shown in Figure 3. The crack parameters are as follows:

Crack depth	2a = 3.2 inch
Crack length	l = 3.8 inch
Crack aspect ratio	a/l = 0.421 inch
Eccentricity	e = 6.4/2 - 1.0 - 1.6 = 0.6 inch
Eccentricity ratio	2e/t = 0.1875

5.4.1 Flaw Stability Analysis

Using the methods of ASME Code, Section XI, IWB-3610 [1], the flaw is evaluated to demonstrate required margins against brittle failure. As discussed in Section 5.2, the allowable fracture fracture toughness for Service Levels A and B is limiting and therefore will be used in determining flaw stability. From Section 5.2 above, an allowable applied stress intensity factor of 69.57 ksi$\sqrt{in}$ or less would maintain the Code required (K_{Ic}/K_I) margin of $\sqrt{10}$ to prevent brittle failure for Service Levels A and B. The stress intensity factor characterizes the crack driving force when using the IWB-3610 linear elastic fracture mechanics methods. The stress intensity factor is a function of applied stress and the crack depth. The applied stress is the sum of the pressure, thermal and weld residual stresses. At the flaw location, no other stresses are expected since the flaw location is remote from discontinuities such as nozzle openings [4]. The **pc-CRACK** results are contained in the computer files Appendix A. The calculated allowable flaw half-depth is 1.7156 inch.

5.4.2 End-of-Life Fatigue Crack Growth Calculation

Since the indication is subsurface and therefore unwetted, the end-of-life flaw size due to fatigue crack growth is calculated using the fatigue crack growth curves for carbon and low alloy ferritic steels exposed to air environments, from Figure A-4300-1 of Appendix A of Reference [1]:

$$da/dN = C_o(\Delta K_I)^n \quad \text{(in/cycle)}$$

$$n = 3.07$$
$$C_o = 1.99\times10^{-10}S$$
$$S = 25.72(2.88-R)^{-3.07} \text{ for } 0\leq R\leq 1$$
$$R = K_{min}/K_{max}$$
$$\Delta K_I = K_{max} - K_{min} \quad (\text{ksi}\sqrt{\text{in}})$$

System cycle counts are obtained from the adjusted 60-year cycle projections [12, Table 4-6]. For all Service Level A/B events, the total annual cycles are 37.25 cycles.

The total stress is considered to cycle between the total of internal pressure (21 ksi), thermal transient (-0.6393x + 5.6602, ksi), and weld residual stress (8 ksi) to a minimum of weld residual stress (8 ksi). The weld residual stress is a constant stress which increases the mean stress.

The fatigue crack growth analysis from **pc-CRACK** is shown in the files listed in Appendix A. The crack size versus number of cycles (da/dN) is shown in Figure 4.

6.0 RESULTS OF ANALYSIS

The results of the **pc-CRACK** flaw stability and crack growth analyses are presented in the files listed Appendix A. These results demonstrate that:

1. The observed flaw is acceptable for continued operation per the requirements of ASME Code, Section XI, IWB-3640 and Appendix A, up to a flaw half-depth of 1.7156 inch (i.e., where $K_{I(allowable)} = 69.57 \text{ ksi}\sqrt{\text{in}}$).
2. Fatigue crack growth of the 1.6-inch flaw to the allowable half-depth of 1.7156 inch would require 70 years.

7.0 SUCCESSIVE INSPECTIONS

As required by ASME Code, Section XI, IWB-3132.3 [1], indications that exceed the acceptance standards of Table IWB-3510-1 but found acceptable for continued operation by the flaw evaluation methods of IWB-3600 must be subsequently re-examined in accordance with IWB-2420(b) and (c). IWB-2420(b) requires that the area containing the flaw shall be inspected during the next three inspection periods listed in the schedule of the inspection program of IWB-2400. ASME Section XI Code Case N-526 [17] provides alternate requirements for re-examination of subsurface flaws found by volumetric examinations in lieu of the requirements in IWB-2420(b). This Code Case is accepted without condition in Regulatory Guide 1.147 Revision 17 [18] and has also been incorporated in recent Editions of ASME Code, Section XI.

Code Case N-526 states that the re-examinations in accordance with IWB-2420(b) of vessel volumes containing subsurface flaws are not required, provided the following are met [18]:

(a) The flaw is characterized as subsurface in accordance with the figure provided in the Code Case (shown in Figure 5).
(b) The NDE technique and evaluation that detected and characterized the flaw, with respect to both sizing and location, shall be documented in the flaw evaluation report.
(c) The vessel containing the flaw is acceptable for continued service in accordance with IWB-3600, and the flaw is demonstrated acceptable for the intended service life of the vessel.

Note that the figure in Code Case N-526 (shown in Figure 5) does not specify which surface (ID or OD) should be used to determine the distance of the flaw from the surface, S. However, the technical basis document [19] for Code Case N-526 indicates that Code Case N-526 was intended to revise the existing Section XI proximity rule for re-examination based on the possibility of exposing the flaw to the reactor coolant, and potentially to accelerated crack growth in case of rupture of the ligament between the flaw and the inside surface. Since the Code Case is not explicit in this regard, the as-found flaw is evaluated using both the ID and OD surfaces per Code Case N-526 as described below.

As shown in Figure 1, the minimum distance to the ID (S_{ID}) and OD (S_{OD}) surfaces for the as-found flaw are S_{ID} = 2.2 inches and S_{OD} = 1 inch, respectively, and the half-flaw depth is a = 1.6 inch. From Figure 5, for the as-found flaw to be classified as a subsurface flaw, the required minimum distance from the surface (S) is 1.6 inches; therefore, per Code Case N-526, the indication is classified as a subsurface indication when S_{ID} is used. However, when S_{OD} is used, the indication is classified as a surface indication per Code Case N-526. Thus, provision (a) in the Code Case as stated above is met when the ID surface is used (as intended in Code Case N-526 per the technical basis document) but is not met when the OD surface is used. Therefore, per the technical basis document [19] for Code Case N-526, subsequent augmented re-examination in accordance with IWB-2420 (b) and (c) is not required for the identified indication. However, since Code Case N-526 does not explicitly specify to use the ID surface to apply the proximity rule, use of the OD surface which has the shortest distance to the flaw is the most conservative interpretation of the Code Case.

8.0 CONCLUSIONS AND DISCUSSION

Based on the flaw evaluation of the indication in the BFN, Unit 2 reactor vessel V-3-A vertical weld using ASME Code Section XI, IWB-3600, it will take 70 years for an as-found flaw with an initial half-depth of 1.6 inch to propagate to the allowable half-depth of 1.7156 inch based on the 48 EFPY fluence.

The initial as-found flaw half-depth and the final allowable flaw half-depth are illustrated in Figure 6:

The initial flaw geometry is:

- half-depth, a = 1.6 inch
- depth, 2a = 3.2 inch
- separation distance from the crack to the surface, S = 1.0 inch

The final flaw geometry is:

- final half-depth, a_f = 1.7156 inch
- final depth, $2a_f$ = 3.4312 inch
- final separation distance from the crack to the surface, S_f = 0.8844 inch

Per the subsurface criteria of ASME Code, Section XI, the rules of IWA-3320 state that flaws may be treated as subsurface if S ≥ 0.4a. Using the final flaw geometry dimensions:

(S = 0.8844 inch) > (0.4a = 0.4×1.7156 inch = 0.6862 inch)

Therefore, the final crack is still treated as subsurface flaw.

From Section 7.0, it has been demonstrated that subsequent augmented re-examinations in accordance with IWB-2420 (b) and (c) of the indication identified in weld V-3-A are not required per the technical basis document [19] for Code Case N-526 using the ID surface to apply the proximity rule. However, since Code Case N-526 does not explicitly specify to use the ID surface to apply the proximity rule, the augmented re-examinations are required when the most conservative interpretation of the Code Case using the OD surface to apply the proximity rule is used.

9.0 REFERENCES

1. ASME Boiler and Pressure Vessel Code, 2007 Edition with 2008 Addenda, Section XI, "Rules for Inservice Inspection of Nuclear Power Plant Components".
2. pc-CRACK, Version 5.0, Structural Integrity Associates, Inc., January 7, 2021.
3. General Electric Hitachi Energy NOI Form No. U2R21-R003, BFN/2, V-3-A, "Ultrasonic Flaw Evaluation in Accordance with ASME Section XI, 2007 Edition, 2008 Addenda". SI File No. 2100264.201.
4. TVA Drawing No. 2-CHM-2046-C-01, Revision 3, "Browns Ferry Nuclear Plant Unit1, Reactor Pressure Vessel, Shell Course Weld/Nozzle Locations (Outside View)" SI File No. 2100264.201.
5. TVA Document No. Form N-1, Unit #2, "Manufacturer's Data Report for Nuclear Vessels", SI File Number 2100264.201.
6. ASME Boiler and Pressure Vessel Code, 2007 Edition with 2008 Addenda, Section II, "Materials-Part D (Customary)".
7. Electric Power Research Institute (EPRI) TR-100251, Research Project 2975-13, "White Paper on Reactor Vessel Integrity Requirements for Level A and B Conditions", January 1993.
8. TVA Document No. 2021-03-08-095538, Browns Ferry Fabrication Report, Page 31 "Vessel Assembly and Internal Attachment Welds", 1/15/93, SI File No. 2100264.201.
9. NEDO-33860, Revision 1, "Safety Analysis Report for Browns Ferry Nuclear Plant Units 1, 2, and 3, Extended Power Uprate", SI File No. 2100264.201.
10. General Electric Hitachi Nuclear Energy Document No. 000N3122-R0, "Tennessee Valley Authority Browns Ferry Unit 1, 2, and 3 Neutron Fluence Evaluation," March 2014. **PROPRIETARY**, SI File No. 2100264.201P.
11. Regulatory Guide 1.99, Rev. 2, Radiation Embrittlement of Reactor Vessel Materials, U.S. Nuclear Regulatory Commission, May 1988.
12. General Electric Hitachi Nuclear Energy Document No. 24A5890, Revision 7, "Reactor Pressure Vessel - Extended Power Uprate" **PROPRIETARY**, SI File No. 2100264.201P.
13. ANSYS Mechanical APDL (UP20170403) and Workbench (March 31, 2017), Release 18.1, SAS IP, Inc.
14. Structural Integrity Associates, Inc. Calculation Package 1201256.301, Revision 0, "Loading for Browns Ferry Feedwater Piping Limiting Fatigue Location", 06/03/2013.
15. General Electric Nuclear Division Doc. No. 22A5584, Revision 1, Browns Ferry II, "Reactor Vessel, Design Specification (Repair)". SI File No. BFN-01Q-229.
16. Structural Integrity Associates, Inc. Calculation Package 1200323.308, Revision 0, "Feedwater Nozzle Design Loads Calculation for Use in Environmental Fatigue Analysis", 06/03/2013.
17. ASME Boiler and Pressure Vessel Code, Code Case N-526, "Alternative Requirements for Successive Inspections of Class 1 and 2 Vessels, Section XI, Division 1," Approved by ASME Code Committee August 9, 1996. Approved in Regulatory Guide 1.147, Revision 17.
18. Regulatory Guide 1.147, "Inservice Inspection Code Case Acceptability, ASME Section XI, Division 1," Revision 17, Nuclear Regulatory Commission, August 2014.

19. N. Cofie, P. Riccardella, J. Merkle and H. Do, “Technical Basis for Alternate Successive Inspection Requirements for Vessels and Piping Welds as Prescribed in Code Cases N-526 And N-735”, Proceedings of ASME Pressure Vessel and Piping Conference, Chicago, IL, July 2008.
20. TVA Document No. 2-SI-3.3.1.A, Revision 0, Page 28 of 170, BFN Unit 2, “ASME Section XI System Leakage Test of Reactor Pressure Vessel and Associated Piping (ASME Section III Class 1 and Class 2)”, 04/13/21. SI File Number: 2100264.201.

Table 1. BFN Unit 2 Weld V-3-A Fast Neutron Fluence and Fracture Toughness Material Properties

Component	48 EFPY Fluence at 0T (n/cm^2)	Cu (wt%)	Ni (wt%)	Chemistry Factor (CF) (°F)	Initial RT_{NDT} (°F)
RPV Vertical Weld, V-3-A	1E17 (1)	0.24(2)	0.37(2)	141(3)	23.1(2)

Notes:

(1) Assumed peak fluence at the I.D. surface (0T) for weld V-3-A (See Section 4.0).
(2) Generic values for ESW materials [9, Table 2.1-2b].
(3) CF value obtained from BFN2 surveillance capsule data for ESW material [9, Table 2.1-2b].

Table 2: Toughness, K_{Ic}, of Vertical Weld V-3-A as a Function of Temperature and RT_{NDT} for 48 EFPY

Temperature, T (°F)	T - RT_{NDT} (°F)	Toughness, K_{Ic} (ksi√in)
-100	-144	34
-90	-134	35
-80	-124	35
-70	-114	35
-60	-104	36
-50	-94	36
-40	-84	37
-30	-74	38
-20	-64	39
-10	-54	40
0	-44	42
10	-34	44
20	-24	46
30	-14	49
40	-4	52
50	6	56
60	16	62
70	26	68
80	36	75
90	46	85
100	56	96
110	66	110
120	76	127
140	96	173
150	106	204
151	107	208
152	108	211
153	109	215
154	110	219
154.25	110	220
175	131	220
200	156	220
300	256	220
400	356	220
500	456	220
600	556	220

Note: 220 ksi√in is the assumed upper shelf cutoff value for the onset of upper shelf toughness.

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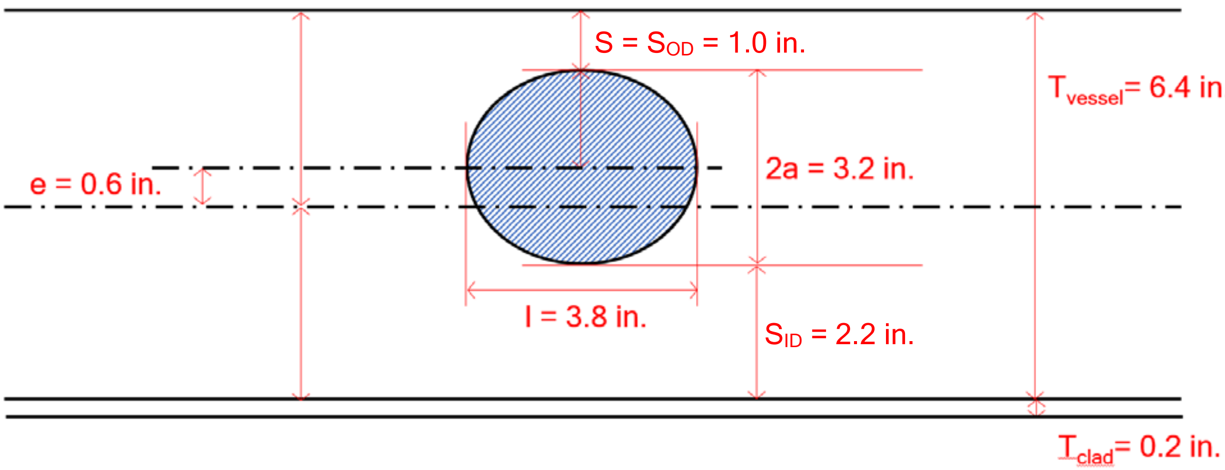


Figure 1. Flaw Geometry [3]

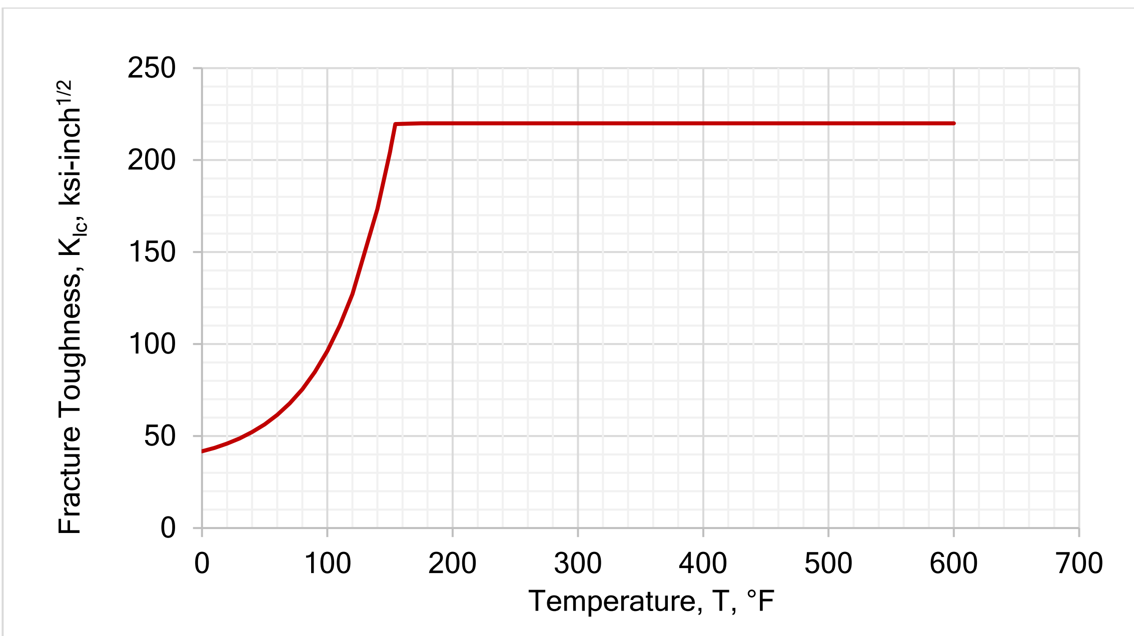


Figure 2. Toughness, K_{Ic}, vs. Crack Tip Temperature for BFN Unit 2 Weld V-3-A through 48 EFPY

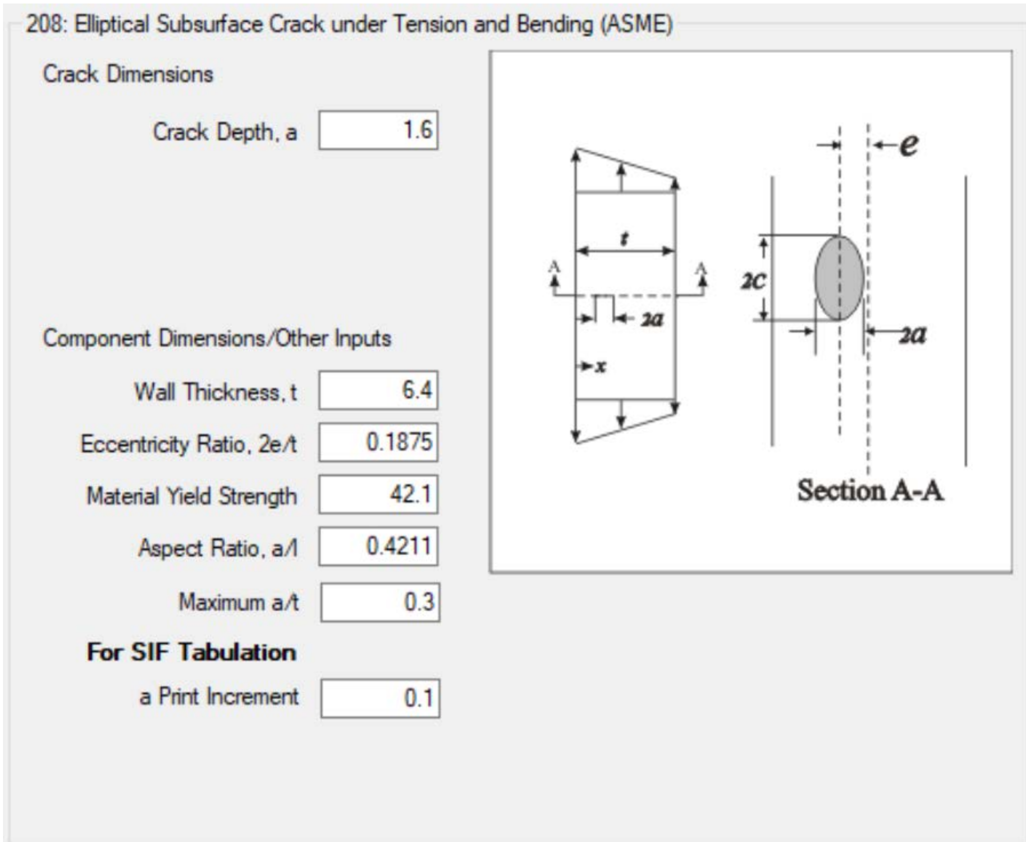
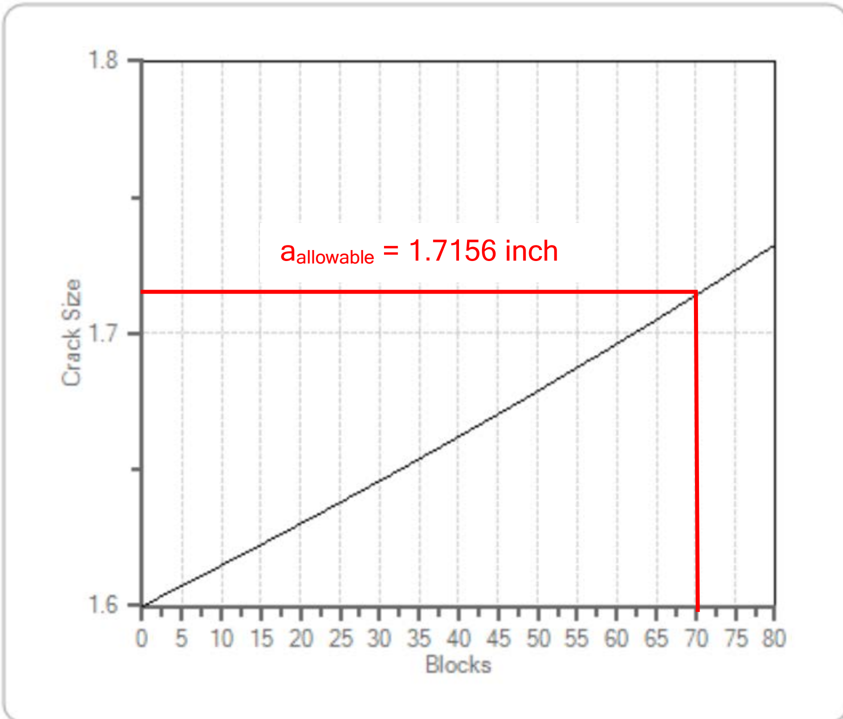


Figure 3. Fracture Mechanics Model



Note: Crack Size = a, which is half flaw-depth in inches
Blocks = years

Figure 4. Fatigue Crack Growth Results from pc-CRACK

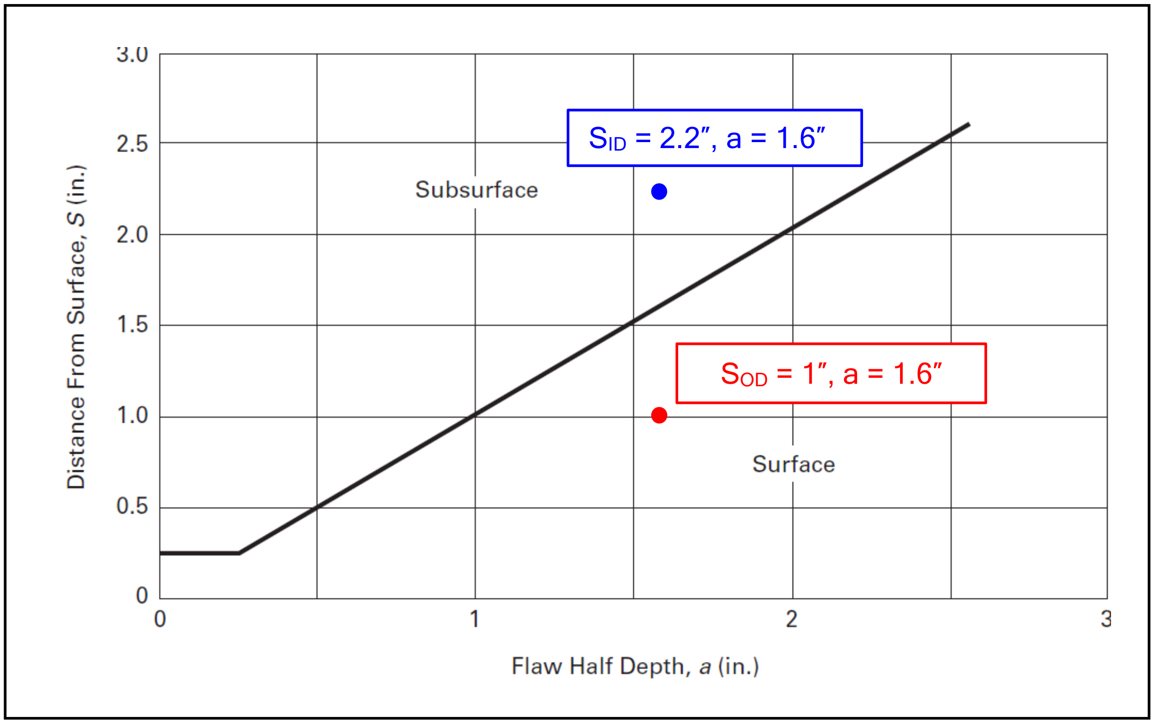


Figure 5. Successive Examination (Surface Proximity Rule) [17]

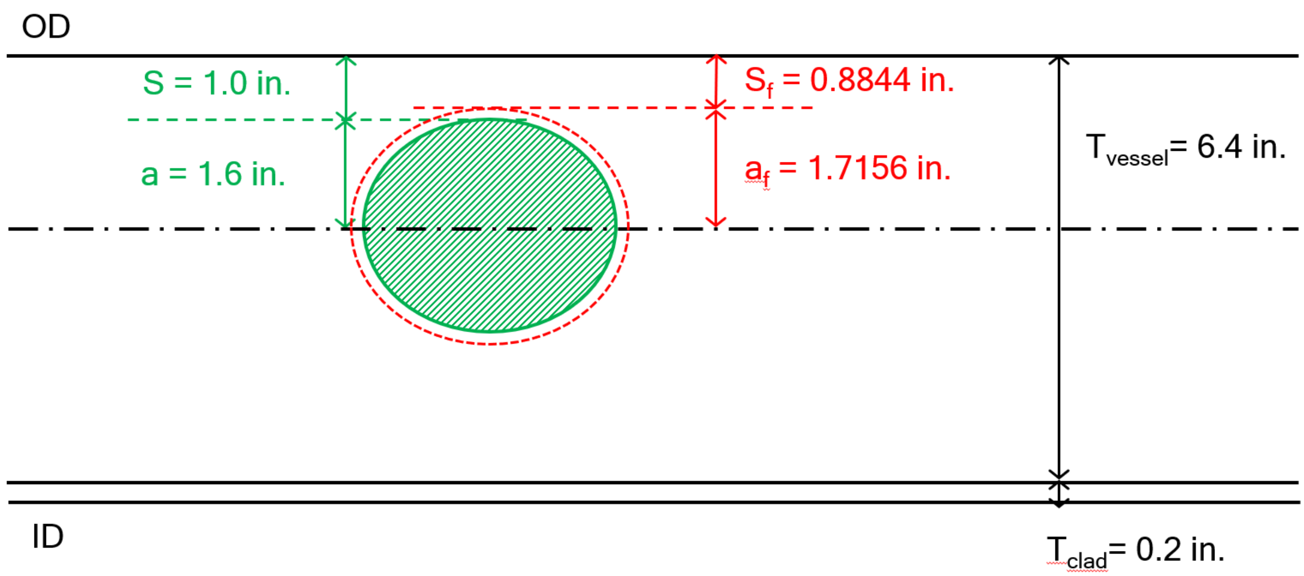


Figure 6. Initial and Final Flaw Geometry

APPENDIX A

COMPUTER FILES

Filename	Description
Critical_CrackSize_AB.pcf	pc-CRACK input file for critical crack size calculation
Critical_CrackSize_AB.kva	pc-CRACK output file: K vs a, for critical crack size calculation
Critical_CrackSize_AB.rpt	pc-CRACK report file, for critical crack size calculation
FCG_subsurface.pcf	pc-CRACK input file for fatigue crack growth calculation
FCG_subsurface.kva	pc-CRACK output file: K vs a, for fatigue crack growth calculation
FCG_subsurface.avc	pc-CRACK output file: a vs c, for fatigue crack growth calculation
FCG_subsurface.avn	pc-CRACK output file: a vs N, for fatigue crack growth calculation
FCG_subsurface.rpt	pc-CRACK report file, for fatigue crack growth calculation

APPENDIX B

THERMAL STRESS ANALYSIS

To determine the thermal stress in the RPV wall, a thermal transient analysis is performed using the ANSYS finite element software [13]. The RPV dimensions are as follows:

- RPV wall thickness: 6.4 inches [3]
- Cladding thickness: 0.2 inch [3]
- RPV inside radius (to base metal): 125.6875 (derived from [5])

Material properties for the SA-302 Grade B vessel wall and the 308L stainless steel cladding are taken from ASME Code, Section II [6] (See Table B-1 and Table B-2). The Service Level A/B RPV transient in Table 4 of Reference [14] with the highest ΔT was chosen as the bounding transient which is the Start-up Transient (See Table B-3). A heat transfer coefficient of 1000 BTU/hr-ft^2-°F for forced convection per Reference [15, sheet 7] is applied to the inside surface of the cladding. The thermal transient definition of the Start-up Transient is shown in Figure B-1. The finite element model is shown in Figure B-2.

Table B-1: SA-302 Grade B, Class 1 Thermal Properties

Temperature [°F]	Young's Modulus [x10^6 psi]	Mean Thermal Expansion [x10^{-6} in/in/°F]	Thermal Conductivity [Btu/hr-ft-°F]	Specific Heat [Btu/lb-°F]	Thermal Diffusivity [ft^2/hr]
-100	30.0	-	-	-	-
70	29.0	7.0	23.7	0.107	0.459
100	28.9	7.1	23.6	0.108	0.451
200	28.5	7.3	23.5	0.115	0.424
300	28.0	7.4	23.4	0.121	0.401
400	27.6	7.6	23.1	0.126	0.379
500	27.0	7.7	22.7	0.131	0.357
600	26.3	7.8	22.2	0.137	0.336

Table B-2: 308L Stainless Steel Thermal Properties

Temperature [°F]	Young's Modulus [x10^6 psi]	Mean Thermal Expansion [x10^{-6} in/in/°F]	Thermal Conductivity [Btu/hr-ft-°F]	Specific Heat [Btu/lb-°F]	Thermal Diffusivity [ft^2/hr]
-100	29.2	-	-	-	-
70	28.3	8.2	8.2	0.118	0.139
100	28.1	8.2	8.3	0.118	0.140
200	27.5	8.5	8.8	0.121	0.145
300	27.0	8.7	9.3	0.124	0.150
400	26.4	8.9	9.8	0.126	0.155
500	25.9	9.1	10.2	0.127	0.160
600	25.3	9.2	10.7	0.129	0.165

Note: 308L cladding material is treated as 309 Stainless Steel (12Cr-12Ni).

Table B-3: Start-up Transient

Time, sec	T, °F [14]	HTC, BTU/hr-ft²-°F [15]
0	100	1000
3600	100	1000
19872	552	1000
23472	552	1000

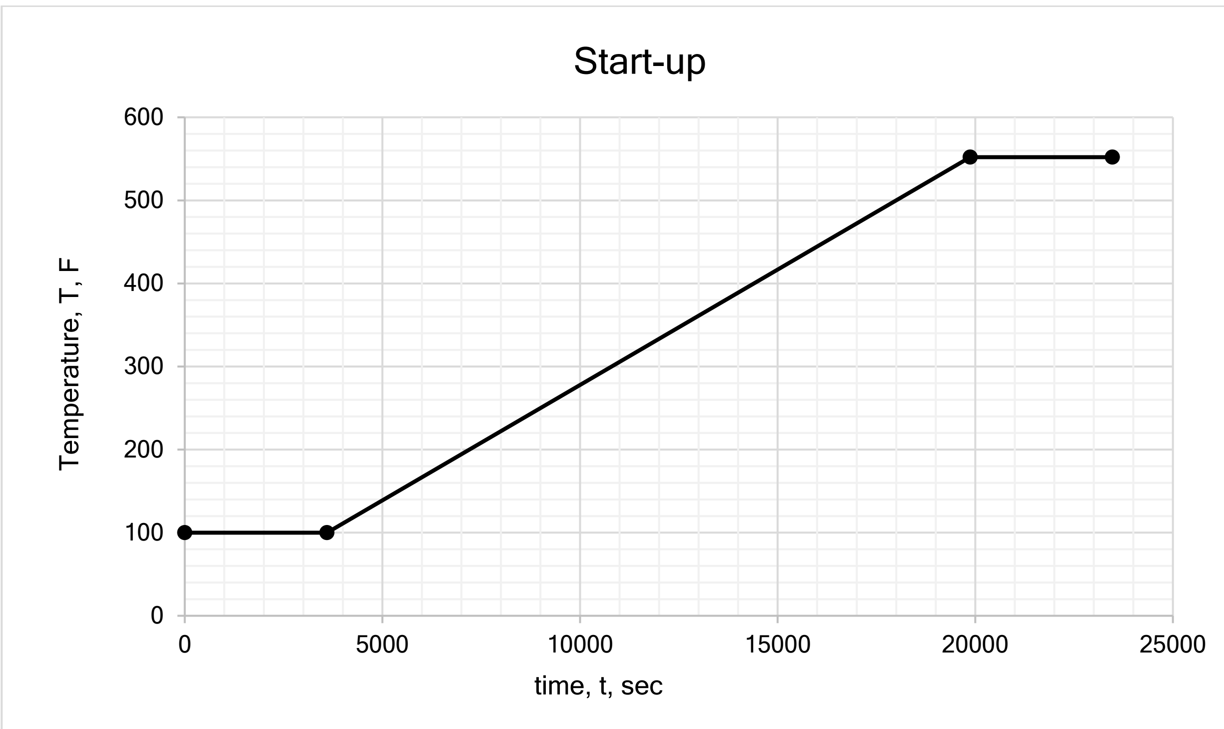


Figure B-1: Thermal Transient Definition

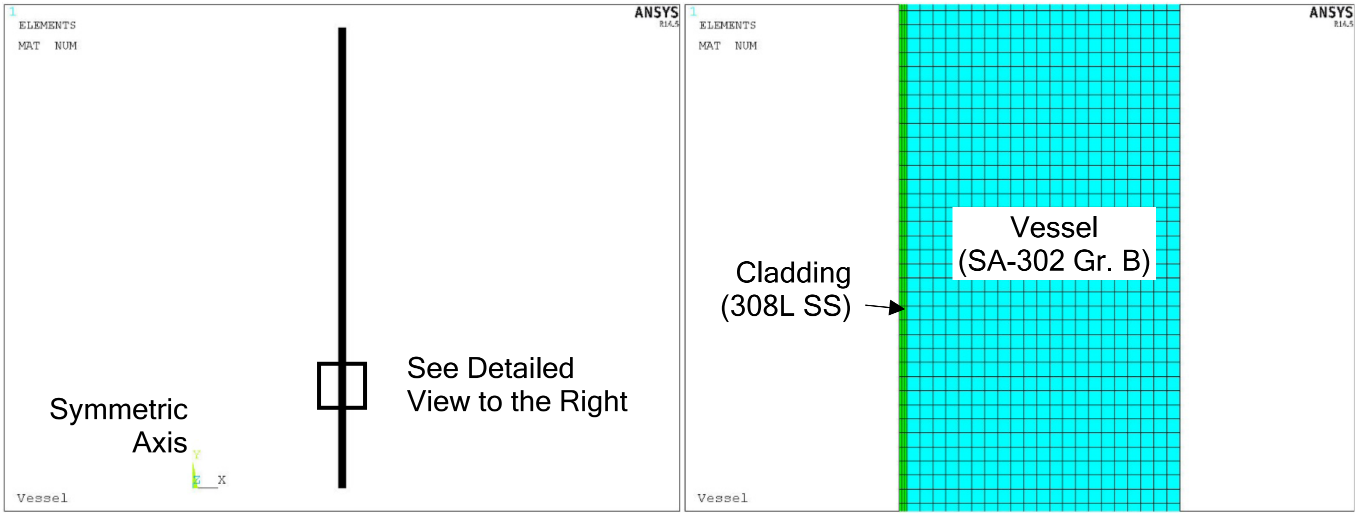


Figure B-2: Finite Element Model

A thermal transient analysis is performed using the temperatures and heat transfer coefficients described previously. An outside vessel temperature of 100°F [16, Section 4.4] is applied with a heat transfer coefficient of 0.2 BTU/hr-ft^2-°F [16, Section 4.5].

Temperatures are transferred to a structural model to perform stress analysis. Hoop stresses ("Z" stress component in ANSYS) are extracted at the 2.2-inch depth and 5.4-inch depth which are the endpoints of the subsurface crack. Figure B-3 shows the nodes used for results post processing (note that Node 9396 is located 2.2" and Node 19092 is located 5.4" into the vessel from the clad/base metal interface). Figure B-4 show the hoop stresses for Node 9396 and Node 19092 during the transient, respectively. Hoop stress at Node 19092 which is the crack-tip near the outside diameter of the RPV bounds the hoop stresses in the subsurface crack. Table B-4 shows all ANSYS input files.

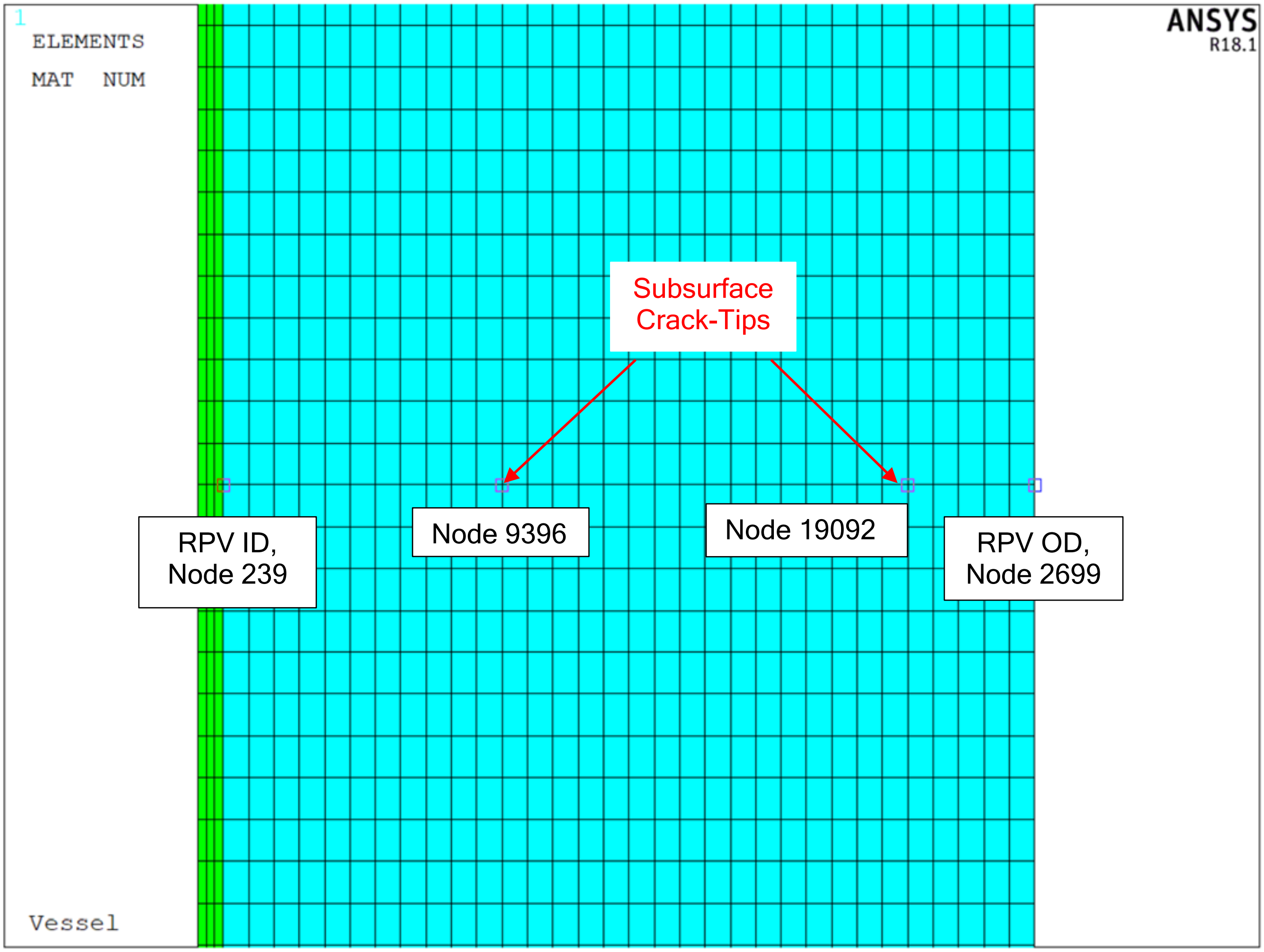


Figure B-3: Nodes used for Results Post-Processing

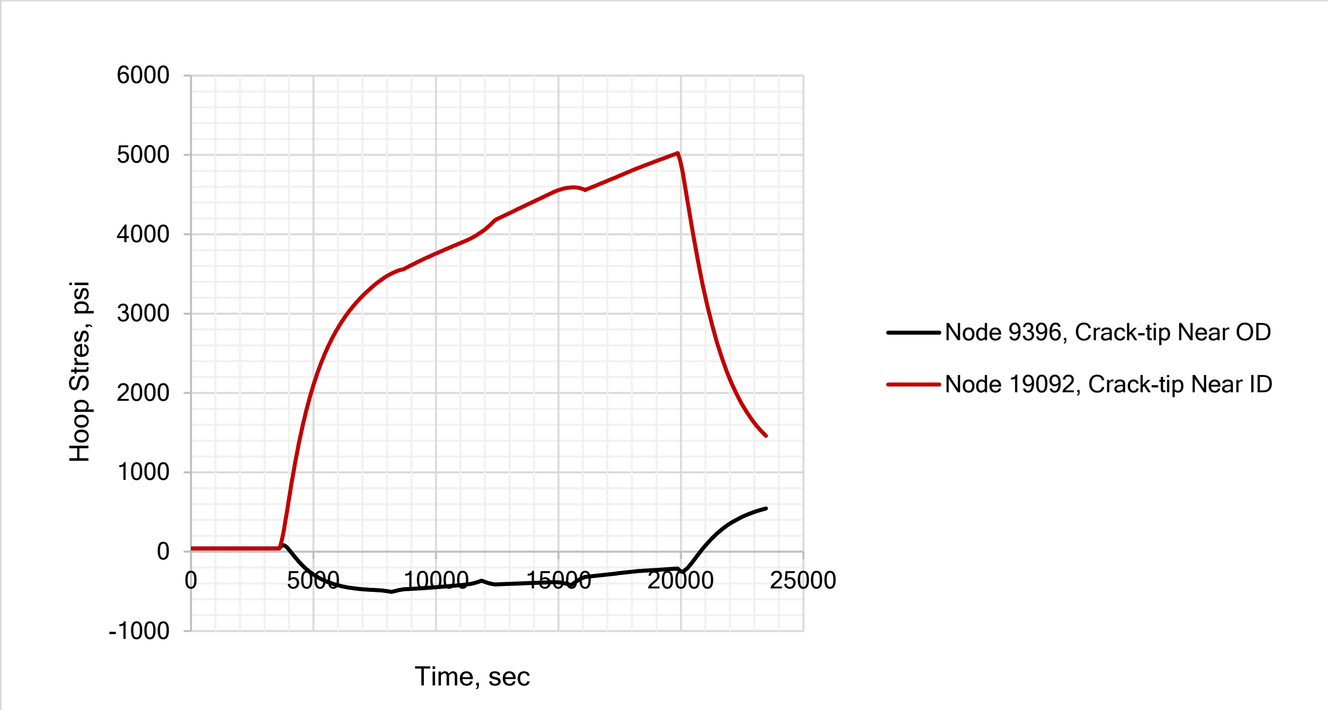


Figure B-4: Hoop Stress During Start-up Transient at Node 9396 and Node 19092

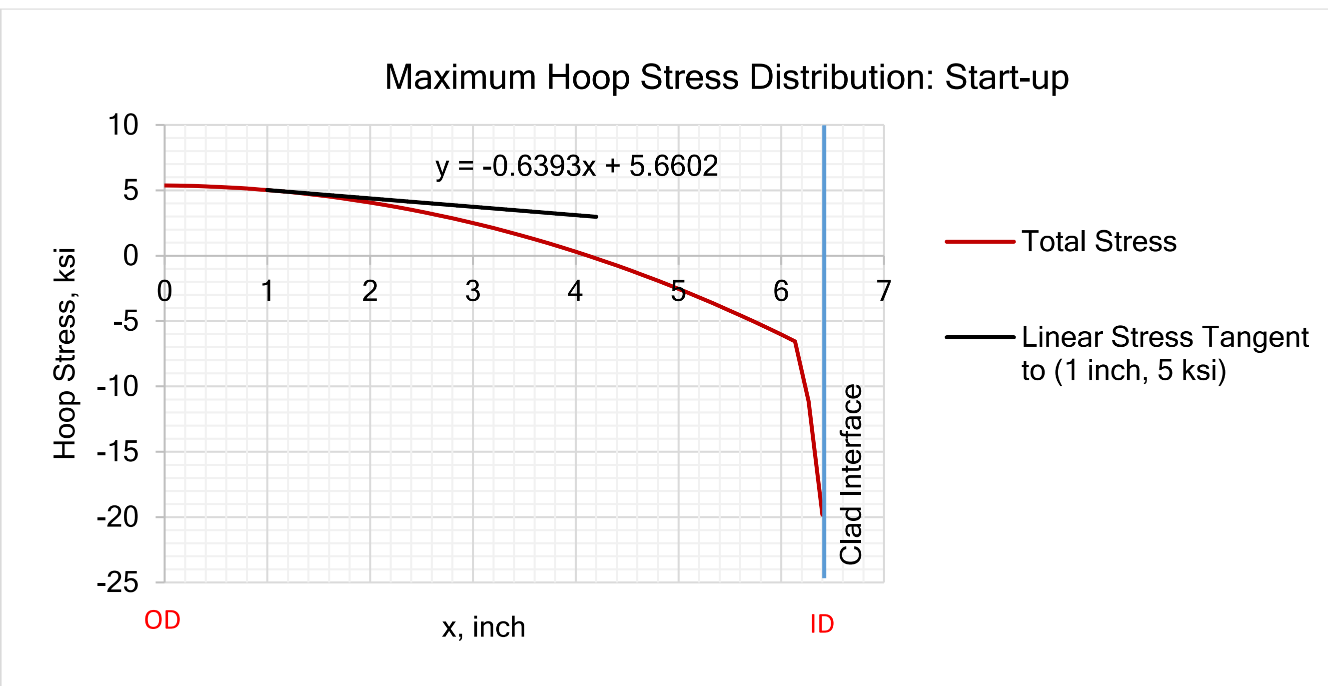


Figure B-5: Start-up, Maximum Stress Distribution at Time = 19872 seconds

From Figure B-4, the maximum hoop stress at the crack-tip near the outside diameter is 5 ksi at 19872 seconds. A hoop stress distribution from outside diameter (x=0) to inside diameter (x=6.4 inch) is plotted in Figure B-5. Since pc-CRACK can only use a linear stress input, a linear stress distribution which is tangent to Point 1-inch by 5 ksi is calculated: $\sigma = -0.6393x + 5.6602$. This linear stress distribution bounds the compressive stress at the inside diameter.

Table B-4: List of ANSYS Files

Filename	Description
Vessel.INP	Creates finite element model of the vessel
Vessel-HTBC.INP	Applies heat transfer boundary conditions
MATPROPS.INP	Contains material properties
HU-T-V.INP	Thermal transient definition and analysis
CMNTR.MAC	Creates monitor file to read in thermal data
HU-T-V_mntr.INP	Monitor file created by CMNTR.MAC
HU-S-V.INP	Thermal stress analysis