ENCLOSURE

ATTACHMENT 4

AREVA NP, INC., DOCUMENT NO. ANP-10308,
"LOW UPPER-SHELF TOUGHNESS FRACTURE MECHANICS
ANALYSIS OF THE
CRYSTAL RIVER UNIT 3 REACTOR VESSEL FOR 54 EFPY"
(NON-PROPRIETARY)

ANP-10308

LOW UPPER-SHELF TOUGHNESS FRACTURE MECHANICS ANALYSIS OF THE CRYSTAL RIVER UNIT 3 REACTOR VESSEL FOR 54 EFPY

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SUMMARY

Appendix G of 10 CFR 50 requires that reactor vessel beltline materials "have Charpy upper-shelf energy ... of no less than 75 ft-lb initially and must maintain Charpy upper-shelf energy throughout the life of the vessel of no less than 50 ft-lb ...." The B&WOG positions on upper-shelf energy for 32 EFPY are documented in the responses to Generic Letter 92-01, as reported in BAW-2166 and BAW-2222, and, the low upper shelf toughness analyses documented in BAW-2148, BAW-2178, and BAW-2192.

Regulatory Guide 1.99, Revision 2, provides two methods for determining Charpy upper-shelf energy (C_VUSE): Position 1 for material that does not have surveillance data available and Position 2 for material that does have surveillance data. For Position 1, the percent drop in C_VUSE, for a stated copper content and neutron fluence, is determined by reference to Figure 2 of Regulatory Guide 1.99, Rev. 2. This percentage drop is applied to the initial C_VUSE to obtain the adjusted C_VUSE. For Position 2, the percent drop in C_VUSE is determined by plotting the available data on Figure 2 and fitting the data with a line drawn parallel to the existing lines that upper bounds all the plotted points.

C_VUSE values were determined for the Crystal River Unit 3 (CR3) reactor vessel beltline materials at 54 EFPY and at 48 EFPY for the rest of B&W plants within the scope of this report. The C_VUSE values for CR3 are maintained above 50 ft-lb for base metal materials (plates and forgings), but drop below the required 50 ft-lb level for the welds. Appendix G of 10 CFR 50 provides for this by allowing operation with lower values of C_VUSE if "it is demonstrated ... that the lower values of Charpy upper-shelf energy will provide margins of safety against fracture equivalent to those required by Appendix G of Section XI of the ASME Code."

Equivalent margins analysis were performed for 48 EFPY and service levels A, B, C, and D for all B&W design plants. These analyses used conservative material models and load combinations, i.e., treating thermal gradient stress as a primary stress. For service levels A through D, the analytical results demonstrate that there is sufficient margin beyond that required by the acceptance criteria of Appendix K of the ASME Code (1992 Edition with 1993 Addenda) [4][1] For service levels A and B, the applied J-integral at 1.15 times the accumulation pressure, plus thermal loadings, is less than the J-integral of the material at a ductile flaw extension of 0.10 inch by a margin of 1.09. For level C and D service loadings, the applied J-integral is less than the J-integral of the material at a ductile flaw extension of 0.10 inch by a margin of 2.26. The criterion for ductile and stable flaw extension is satisfied for Levels A, B, C, and D service loadings. The evaluations for all service levels conclusively demonstrate adequate margins of safety against fracture for the reactor vessels within the scope of these reports.

Based on a reconciliation process it has been established that the equivalent margins analyses for the reactor vessel welds are also applicable for the Crystal River Unit 3 reactor vessel welds at 60 years (54 EFPY). The applicable code year for CR3 is the 2001 Edition including 2003 addenda [4a]. Calculation of the material J-integral at 54 EFPY shows that weld SA-1526 at

[1] Numbers in brackets are references, which are listed in Section 9

Three Mile Island Unit 1 (TMI-1) continues to be limiting and bounds CR3 at 60 years (54 EFPY). Therefore, it can be concluded that the CR3 beltline welds have adequate upper-shelf toughness and satisfy the requirement of Appendix G to 10 CFR 50 at 60 years (54 EFPY).

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1. INTRODUCTION

To qualify reactor vessels for use beyond their original licensing period, an evaluation of materials with upper-shelf Charpy impact energy levels that have dropped or are predicted to drop below 50 ft-lb must be performed to satisfy the requirements of Appendix G to 10 CFR Part 50, which states in Paragraph IV.A.1.a that, "Reactor vessel beltline materials must have Charpy upper-shelf energy ... of no less than 75 ft-lb initially and must maintain Charpy upper-shelf energy throughout the life of the vessel of no less than 50 ft-lb, unless it is demonstrated in a manner approved by the Director, Office of Nuclear Reactor Regulation, that lower values of Charpy upper-shelf energy will provide margins of safety against fracture equivalent to those required by Appendix G of Section XI of the ASME Code." Materials with Charpy upper-shelf energy below 50 ft-lbs are said to have low upper-shelf (LUS) fracture toughness.

This topical report addresses the Charpy Upper-Shelf Energy (USE) requirements of 10 CFR part 50, Appendix G by providing the evaluation which demonstrates that for an extended license period of CR3, corresponding to 54 EFPY, the weld metals which are expected to have low upper-shelf (LUS) energy will have margins of safety against fracture equivalent to Appendix G of the ASME Code in accordance with Appendix G of 10 CFR 50. A similar analysis was performed for the 32 EFPY end-of-license periods [1, 2] which was reviewed and approved by the NRC. A fracture mechanics analysis is not required for the reactor vessel plate and forging materials within the beltline region since all applicable materials are predicted to have Charpy upper-shelf energies in excess of 50 ft-lb at 60 years (54 EFPY) (Tables 4-3 through 4-7 of Reference 3).

The analysis covers Level A, B, C, and D Service Loads, and was performed according to the acceptance criteria and evaluation procedures of Appendix K of the ASME Boiler and Pressure Vessel (B&PV) Code, Section XI [4]. Satisfying the requirements of Appendix K will provide margins of safety against fracture equivalent to those required by Appendix G. It should be noted that the stress intensity factor solutions in the 32 EFPY end-of-license period analyses for Level A and B Service Loads [1] are slightly different from those in Appendix K of the Code since the 32 EFPY analyses was performed prior to the issuance of Appendix K.

Appendix K specifies evaluation procedures and acceptance criteria for Level A, B, C, and D Service Loads. The method used for evaluation of Level C and D Service Loads is based on the AREVA NP computer code PCRIT which uses a one-dimensional finite element model for thermal and stress analysis and linear-elastic fracture mechanics analysis methods.

Based on a reconciliation process it has been established that the equivalent margins analyses for the reactor vessel welds are also applicable for the Crystal River Unit 3 reactor vessel welds at 60 years (54 EFPY). The applicable code year for CR3 is the 2001 Edition including 2003 addenda [4a]. Calculation of the material J-integral at 54 EFPY shows that weld SA-1526 at Three Mile Island Unit 1 (TMI-1) continues to be limiting and bounds CR3 at 60 years (54 EFPY). Therefore, it can be concluded that the CR3 beltline welds have adequate upper-shelf toughness and satisfy the requirement of Appendix G to 10 CFR 50 at 60 years (54 EFPY).

The analysis in this document is a bounding analysis of the reactor vessels considered, combining the most limiting weld within each vessel with the most limiting loading conditions to show that welds of the reactor vessels listed in Table 1-1 are acceptable.

Table 1-1 Reactor Vessels Considered in this Analysis

Utility	Unit
Florida Power Corporation (Progress Energy Florida)	Crystal River - 3
Duke Power Company	Oconee - 1 Oconee - 2 Oconee - 3
GPU Nuclear Corporation (Exelon)	Three Mile Island - 1
Entergy Operations, Inc.	ANO - 1

2. ANALYTICAL METHODOLOGY

2.1 Acceptance Criteria

The acceptance criteria for demonstrating adequacy of RV weld metal upper-shelf toughness are specified in Article K-2000 of reference [4]. These criteria are restated below as they pertain to the evaluation of reactor vessel weld metal (criteria pertaining to RV base metal are excluded).

2.1.1 Level A and B Conditions

a) When evaluating adequacy of the upper-shelf toughness for the weld material for Levels A and B Service Loadings, an interior semi-elliptical surface flaw with a depth one-quarter of the wall thickness and a length six times the depth shall be postulated (i.e., aspect ratio of 0.167), with the flaw's major axis oriented along the weld of concern and the flaw plane oriented in the radial direction. Two criteria shall be satisfied:

   1) The applied J-integral evaluated at a pressure 1.15 times the accumulation pressure (P_a) as defined in the plant-specific Overpressure Protection Report, with a factor of safety of 1.0 on thermal loading for the plant specific heatup and cooldown conditions, shall be less than the J-integral of the material at a ductile flaw extension of 0.10 inch.

   2) Flaw extension at pressures up to 1.25 times the accumulation pressure (P_a) shall be ductile and stable, using a factor of safety of 1.0 on thermal loading for plant specific heatup and cooldown conditions.

b) The J-integral resistance versus flaw extension curve shall be a conservative representation for the vessel material under evaluation.

2.1.2 Level C Conditions

a) When evaluating the adequacy of the upper-shelf toughness for the weld material for level C Service Loadings, interior semi-elliptical flaws with depths up to one-tenth of the base metal wall thickness, plus the cladding thickness, with total depths not to exceed 1.0 inch, and a surface length six times the depth shall be postulated, with the flaw's major axis oriented along the weld of concern and the flaw plane oriented in the radial direction. Flaws of various depths, ranging up to the maximum postulated depth, shall be analyzed to determine the most limiting flaw depth. Two criteria shall be satisfied.

   1) The applied J-integral shall be less than the J-integral of the material at a ductile flaw extension of 0.10 in., using a factor of safety of 1.0 on loading.

   2) Flaw extensions shall be ductile and stable, using a factor of safety of 1.0 on loading.

b) The J-integral resistance versus flaw extension curve shall be a conservative representation for the vessel material under evaluation.

2.1.3 Level D Conditions

a) When evaluating adequacy of the upper-shelf toughness for Level D Service Loadings, flaws as specified for Level C Service Loadings (above) shall be postulated and toughness properties for the corresponding orientation shall be used. Flaws of various depths, ranging up to the maximum postulated depth, shall be analyzed to determine the most limiting flaw depth. Flaw extensions shall be stable, using a factor of safety of one on loading.

b) The J-integral resistance versus flaw extension curve shall be a best estimate representation for the vessel material under evaluation.

c) The extent of stable flaw extension shall be less than or equal to 75% of the vessel wall thickness, and the remaining ligament shall not be subject to tensile instability.

2.2 Temperature Range for Upper-Shelf Fracture Toughness

Fracture toughness can be addressed in three different regions on the temperature scale, i.e. upper-shelf toughness region, transition region, and lower-shelf toughness region. Upper-shelf fracture toughness is determined by Charpy V-notch impact energy versus temperature plots by noting the temperature above which the Charpy impact energy remains at a relatively constant energy level. Fracture toughness of reactor vessel steel and associated weld metals are conservatively predicted by the ASME initiation toughness curve, K_{Ic}, in the lower-shelf and transition regions. The upper-shelf toughness curve, K_{Jc}, is used in the upper-shelf region. The K_{Jc} curve in this analysis is derived from the low upper-shelf J model used in references [1] and [2].

2.3 Fracture Mechanics Analysis Methods

2.3.1 Level A and B Service Loads

Article K-4000 specifies the method for evaluating reactor vessel welds subject to Level A and B Service Loads [4].

The loading considered is pressure equal to 110 percent of design pressure combined with a 100 °F/hr thermal gradient load. A flaw with a depth equal to 25 percent of the RV wall is postulated and the applied J-integral and material J-integral resistance are calculated and compared at a flaw extension of 0.1 inch. Stability of flaw extension is also evaluated by examining the relationship of the applied J-integral and material J-integral curves. Section 5 contains the details of this analysis.

2.3.2 Level C and D Service Loads

The 1992 through 1993 version of Appendix K [4] does not specify a method for the calculation of the applied J-integral, however, AREVA NP has extensive experience in this area and has written a computer code, PCRIT, to perform the calculations of the applied stress intensity factor for each of the transients considered. The transients considered are those which have the potential to cause the largest thermal gradients, and therefore, cause the greatest crack driving force.

PCRIT has a one-dimensional finite element model for thermal and stress analyses and linear-elastic fracture mechanics analysis capabilities for both longitudinal and circumferential semi-elliptical surface flaws.

The effect of the differential thermal expansion between the reactor vessel base metal and the cladding on the fracture mechanics analysis must be considered separately. The PCRIT code accounts for the cladding in the thermal analysis (calculation of temperature versus time), but not in the fracture mechanics analysis. To account for the cladding, K_{Iclad} is separately calculated and added to the total applied K_I, calculated by PCRIT, using the principle of superposition.

The 2001 through 2003 version of Appendix K [4a] specifies a method for the calculation of the applied J-integral which is the same as that employed by AREVA using PCRIT. The analysis for Level C and D Service Loads, contained in Section 6, may therefore also be used to evaluate the CR3 beltine welds at 60 years (54 EFPY).

3. MATERIAL PROPERTIES

3.1 J-Resistance Model for Mn-Mo-Ni/Linde 80 Welds

The J-resistance model for the Mn-Mo-Ni/Linde 80 welds in the reactor vessels considered here was developed by the B&W Owners Group using a large J-resistance data base. This model is described in (Appendix B) of Reference 1 and is programmed into the PCRIT computer program.
The current model form of the J-R equation is obtained as follows:

$$J = C1\,(\Delta a)^{C2}\exp(C3\,\Delta a^{C4})$$

where
$\ln C1 = a1 + a2\,Cu(\phi t)^{a7} + a3\,T + a4\,\ln B_N$
$C2 = d1 + d2\,\ln C1 + d3\,\ln B_N$
$C3 = d4 + d5\,\ln C1 + d6\,\ln B_N$
$C4$ = constant (model parameter)

where
Cu = copper content, weight %
T = temperature, °F
ϕt = fluence, 10^{-18} n/cm^{2}*
B_N = net specimen thickness, inches

All model parameters (a, d, C4, etc.) are provided in Table 3-1.

3.2 Mechanical Properties of Weld Materials

Unless noted otherwise, the following irradiated mechanical properties of reactor vessel weld metals [6] are used for this evaluation.

Yield Strength	$\sigma_y = 71.0$ ksi
Young's Modulus	$E = 27{,}450$ ksi (at 550°F)

3.3 Comparison of B&WOG J_d Model and Additional Fracture Toughness Data

The model used to calculate the J-integral resistance has been shown to be a conservative representation of the materials in question for fluence values ranging up to those corresponding to 32 EFPY. Since the development of the B&WOG J_d model, additional specimens from capsules irradiated to greater fluence levels have been tested (see Table 3-2). The data obtained from these test specimens is compared with the B&WOG J_d model in Figure 3-1 to demonstrate the adequacy of the model for fluence levels beyond those which have been examined in previous studies. In Figure 3-1, the predicted J-integral at 0.1 inch crack extension by the B&WOG J_d model is shown as a function of fluence. The additional specimens have been

*Note: Fluence is reported as 10^{-19}n/cm^{2} throughout the remainder of this document.

subjected to a level of fluence greater than 1.38 x 10^{19}n/cm^2 which is the maximum predicted fluence for 48 EFPY [3] at the internal surface of the ANO-1 vessel (See Table 6-1).

In all cases, the J-integral resistance of the test specimens is conservatively bounded by the J_d(lower bound) model.

Table 3-1 Parameters in B&WOG J_d Model

Table 3-2 J-Integral Resistance of Test Specimens

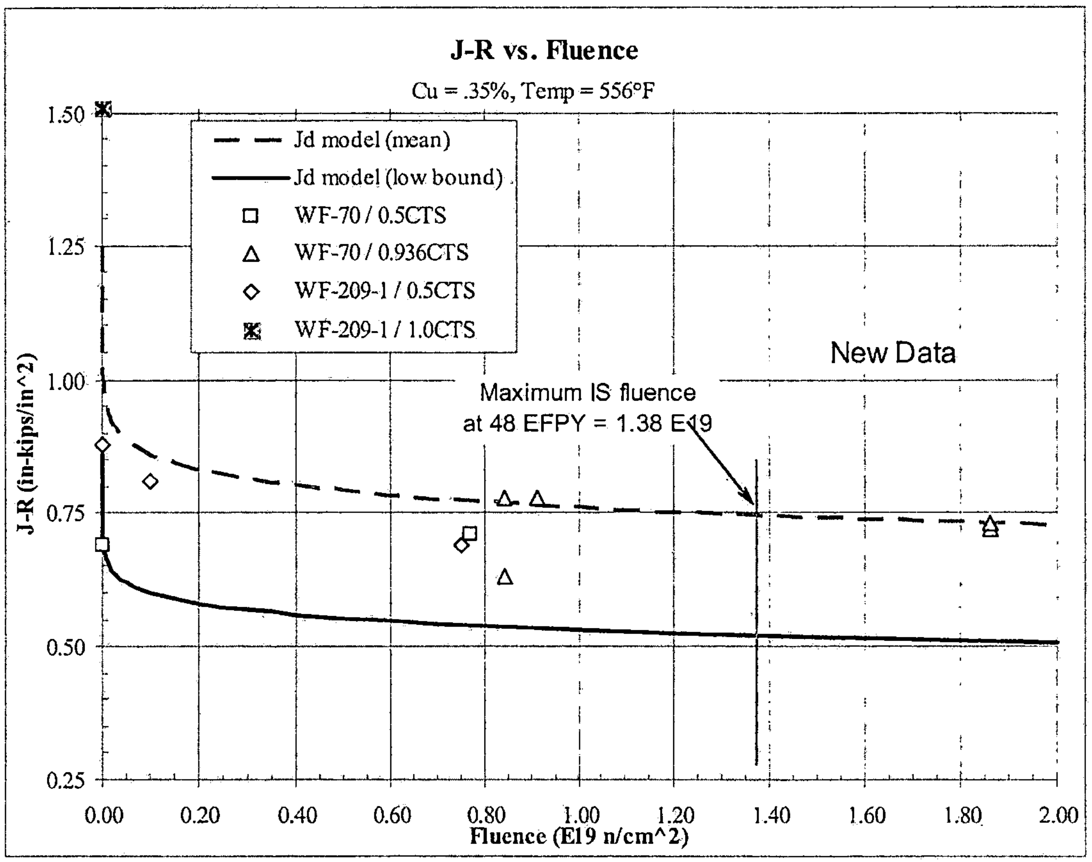
Material	Reference	Specimen		Fluence x10^{-19} (n/cm^2)	Test Temp. (^{o}F)	$J_{0.1}$ (kips/in)
		Number	Type			
WF-70	[5]	66W-129	1/2T CT†	0	550	0.69
	[5]	PR105	1/2T CT	0.771	550	0.71
	[5]	PR070	0.936RCT‡	0.913	550	0.78
	[6]	PR072	0.936RCT	1.86*	550	0.72
	[6]	PR076	0.936RCT	1.86*	550	0.73
	[7,8]	PR73	0.936RCT	0.845	550	0.63
	[7,8]	PR81	0.936RCT	0.845	480	0.78
	[7,8]	PR100	1/2T CT	0.845	480	0.59
WF-209-1	[9]	NN006	1/2T CT	0.10	550	0.81
	[9]	NN019	1/2T CT	0	550	0.88
	[10]	NN007	1/2T CT	0.750	480	0.69
	[9]	NN005T	1T CT	0	430	1.51

* Recent data at higher fluence level.

† CT - Compact Tension

‡ RCT - Round Compact Tension

Figure 3-1 Irradiated Specimen Data Compared with B&WOG J_d Model



4. REACTOR VESSEL WELDS

The J-resistance model presented in Section 3 is a function of fluence, temperature, copper content, and the specimen thickness. Since the applied J-integral for Level A & B Service Loading is the same for all welds having the same orientation, the limiting weld for a reactor vessel is determined by the copper content and the fluence level. The potential limiting welds in each reactor vessel are listed in Table 4-1. Copper content for each weld is obtained from Reference 2, and fluence at the T/4 location is obtained from Tables 4-3 through 4-7 of Reference 3. Some vessels show more than one weld in cases where the choice for the limiting weld is not so obvious due to the two influencing parameters, i.e., copper content and fluence. In a reactor vessel which has both longitudinal and circumferential welds, a longitudinal weld is more limiting than a circumferential weld because there is a factor of two on the hoop stress due to pressure.

The most limiting weld for Level A and B Service Loads is identified in Section 5.3. The most limiting weld for Level C and D Service Loads is identified in Section 6.1.

Table 4-1 Potential Limiting Welds

Plant	Weld Identification	Weld Orientation*	Copper (% weight)	Fluence at T/4 $x10^{-19}$ (n/cm^2)
Oconee-1	SA-1229	C	0.26	0.622
	SA-1585	C	0.21	0.678
	SA-1430	L	0.20	0.571
Oconee-2	WF-25	C	0.35	0.745
Oconee-3	WF-67	C	0.24	0.728
TMI-1	WF-25	C	0.35	0.700
	SA-1526	L	0.35	0.655
CR3	WF-70	C	0.32**	0.912**
	WF-8, 18	L	0.19**	0.842**
ANO-1	WF-182-1	C	0.24	0.711
	WF-112	C	0.31	0.773
	WF-18	L	0.20	0.582

*C = Circumferential, L = Longitudinal, **Data are for 60 years (54 EFPY)

5. EVALUATION FOR LEVEL A AND B SERVICE LOADINGS

As specified in Article K-2000 of ASME Section XI, Level A and B Service Loadings consist of the accumulation pressure (accumulation pressure is 110% of design pressure) and plant specific heatup and cooldown transients. Only cooldown transients need to be considered since heatup transients cause compressive stresses on the interior surface of the reactor vessel, which is where the flaw is postulated to be located.

5.1 Applied J-Integral - Level A and B Service Loads

The applied J-integral during Level A and B Service Loads is calculated using the procedures specified in paragraph K-4210.

Calculation of the applied J-integral consists of two steps: Step 1 calculates the effective flaw depth, including a plastic zone correction; and Step 2 calculates the J-integral for small scale yielding based on this effective flaw depth.

The stress intensity factor due to internal pressure loading, K_{Ip}, is dependent on reactor vessel geometry and postulated flaw orientation, depth, and shape (aspect ratio of 0.167 in accordance with Appendix K). The stress intensity factor due to thermal loading, K_{It}, is also dependent on cooldown rate, but is independent of postulated flaw orientation.

The effective flaw depth, a_e, is calculated using the following equation:

$$a_e = a + (1/6\pi)[K_{Ip} + K_{It})/\sigma_y]^2$$

The stress intensity factors using the effective flaw depth are designated with a prime, e.g., K'_{Ip}, K'_{It} to distinguish from those with a flaw depth of "a". All stress intensity factors are calculated using equations 1, 2, and 3 in Article K-4000.

The applied J-integral is then calculated from the relationship:

$$J = \frac{1000(K'_{Ip} + K'_{It})^2}{E'}$$

where $E' = E/(1-\nu^2)$.

The J-integral due to applied loads, J_1, shall be calculated as stated above using a flaw depth a of 0.25t + 0.10 inch with a plastic zone correction, a pressure p equal to the accumulation pressure for Level A and B Service Loadings, P_a, and a safety factor (SF) of 1.15.

Table 5-1 lists all the required input for Level A and B Service Loads analysis. Table 5-2 lists the calculated applied J-integral for each weld, along with some intermediate quantities used in its calculation.

5.2 Calculation of Material J-Integral Resistance ($J_{0.1}$)

$J_{0.1}$ is the material J-integral resistance at a crack extension of 0.1 inch. It is calculated for each material using the model used in references [1] and [2]. In this model, J is a function of temperature (T), percent copper (%Cu), fluence (f=ϕ t) at the crack tip, crack extension (Δa), and effective specimen thickness (B_N). The specimen thickness size is fixed to 1T CT specimen which has a B_N value of 0.8. The crack extension is also fixed at 0.1 inch by Article K-2000. The values of %Cu and f are listed for each weld in Table 5-3.

Since the Code only requires pressure and a 100°F/hour cooldown from normal operation, the design base cold leg temperature is used for all six plants (i.e., T = 556°F).

The end-of-life (EOL) fluence values are calculated assuming an extended life of 48 EFPY. The fluence attenuation is calculated using the attenuation model in Regulatory Guide 1.99, Rev. 2 [11], i.e.,

$$f = f_{IS}\, e^{-0.24x}$$

where

f_{IS}	is the inner surface fluence, n/cm^2.
x	is the depth into the RV wall, in.
f	is the attenuated fluence at depth x, n/cm^2.

5.3 Acceptance Criteria Assessment

5.3.1 Criterion on J (Article K-2200 (a) (1))

Acceptance criteria for Levels A and B Service Loadings based on a ductile flaw extension of 0.10 inch are satisfied when

$$J_1 < J_{0.1}$$

where

J_1 = the applied J-integral for a safety factor of 1.15 on pressure and a safety factor of 1.0 on thermal loading.

$J_{0.1}$ = the J-integral resistance at a ductile flaw extension of 0.1 inch.

As Table 5-3 shows, the limiting weld is the TMI-1 SA-1526 because its value of $J_{0.1}/J_1$ is the lowest of all the welds considered. Since this ratio is greater than unity, the criterion on the limit of the applied J-integral is satisfied.

5.3.2 Criterion on Flaw Stability (Article K-2200 (a)(2))

The acceptance criterion for flaw stability states that flaw growth at a pressure of 1.25 times the accumulation pressure shall be ductile and stable using a factor of safety of 1.0 on thermal loading.

Subarticle K-3400 states that the equilibrium equation for stable flaw extension is

$$J = J_R$$

where J is the J-integral due to applied loads for the postulated flaw in the vessel, and J_R is the J-integral resistance to ductile tearing for the material.

The inequality for flaw stability due to ductile tearing is

$$\frac{\partial J}{\partial a} < \frac{dJ_R}{da}$$

where $\partial J/\partial a$ is the partial derivative of the applied J-integral with respect to flaw depth, *a*, with constant load, and dJ_R/Da is the slope of the J-R curve. Under increasing load, stable flaw extension will continue as long as $\partial J/\partial a$ remains less than dJ_R/da.

Paragraph K-4310 states that the applied J-integral shall be calculated in the same manner as previously done with the exception that the safety factor on pressure is 1.25 rather than 1.15. The material J-integral resistance curve is constructed using the model discussed in Section 3.

Flaw stability at a given applied load is demonstrated when the slope of the applied J-integral curve is less than the slope of the J-R curve at the point on the J-R curve where the two curves intersect. Figure 5-1 is a plot of the applied J-integral and the lower bound J-R curve of SA-1526. This weld is the limiting weld as discussed in Section 5.3, therefore, if this weld satisfies the stability criterion of this section, all welds will be acceptable.

As Figure 5-1 illustrates, the applied J-integral with a safety factor of 1.25 on pressure, has a slope which is less than the slope of the J-R curve at their intersection point (Δa = 0.17), demonstrating that flaw extension would be ductile and stable, satisfying the second criterion of Appendix K for Level A and B Service Loads.

Figure 5-1 also verifies that at a flaw extension of 0.10 inch, the applied J integral with a safety factor of 1.15 on pressure is less than the J-integral resistance calculated in accordance with the model (as previously demonstrated in Section 5.3.).

Table 5-1 Input for Applied J-Integral Analysis of Six Reactor Vessels for Level A and B Service Loads

DESCRIPTION	INPUT DATA
Inside Radius, Ri	85.5 inch
Thickness, t	8.44 inch
Cold Leg Temperature	556°F
Design Pressure	2500 psi
Maximum Cooldown Rate	100°F/hour

Table 5-2 Applied J-Integral - Level A and B Loads

Plant	Weld Ident./Orient.		K_{Ip} (ksi√in)	K_{It} (ksi√in)	a_e (in.)	F_1^* or F_2^* †	F_3^*	K'_{Ip} (ksi√in)	K'_{It} (ksi√in)	J_I (lbs/in)
Oconee-1	SA-1229	C	49.01	21.99	2.263	0.972	1.062	49.73	21.98	170
	SA-1585	C	49.01	21.99	2.263	0.972	1.062	49.73	21.98	170
	SA-1430	L	97.48	21.99	2.360	1.061	1.060	101.66	21.94	506
Oconee-2	WF-25	C	49.01	21.99	2.250	0.972	1.062	49.55	21.98	170
Oconee-3	WF-67	C	49.01	21.99	2.256	0.972	1.062	49.64	21.98	170
TMI-1	WF-25	C	49.01	21.99	2.250	0.972	1.062	49.55	21.98	170
	SA-1526	L	97.48	21.99	2.339	1.059	1.061	101.08	21.95	502
CR3	W-70	C	49.01	21.99	2.248	0.972	1.062	49.52	21.98	169
	WF-8, 18	L	97.48	21.99	2.360	1.061	1.060	101.66	21.94	506
ANO-1	WF-182-1	C	49.01	21.99	2.263	0.972	1.062	49.73	21.98	170
	WF-112	C	49.01	21.99	2.263	0.972	1.062	49.73	21.98	170
	WF-18	L	97.48	21.99	2.360	1.061	1.060	101.66	21.94	506

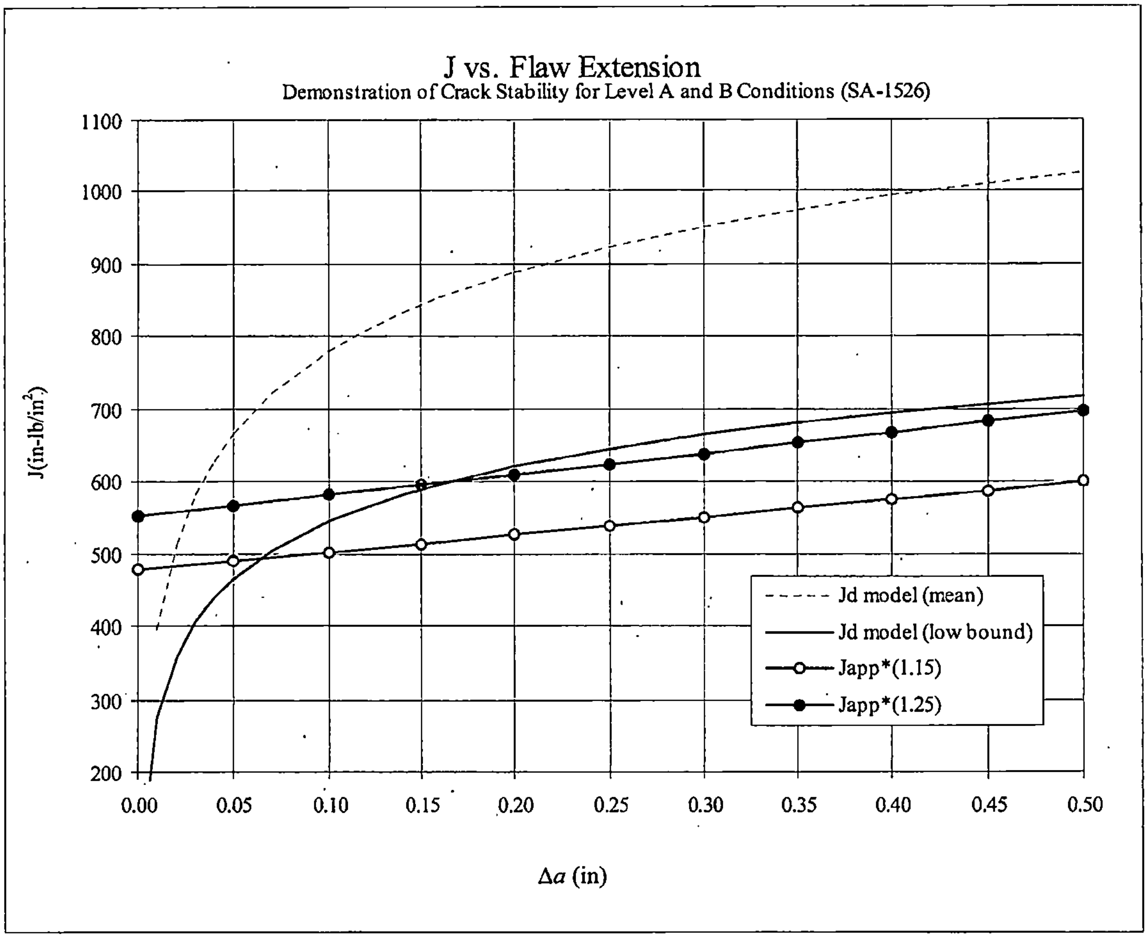
† F_1^* for axial flaws, F_2^* for circumferential flaws (the asterisk (*) signifies that a_e was used in the calculation of the F factors rather than a).

Table 5-3 J-Resistance Value at a Flaw Depth for Service Level A & B Load Analysis.

Plant	Limiting Welds				Fluence at T/4 x 10^{-19} (n/cm^2)	$J_{0.1}$ (lb/in)		Comparison	
	Weld Identification	**Weld Orient.**	**Cu (wt%)**	**Ni (wt%)**		**Mean**	**Lower Bound**	J_1	$\frac{J_{0.1}}{J_1}$
Oconee-1	SA-1229	C	0.26	0.61	0.622	882	616	170	**3.62**
	SA-1585	C	0.21	0.59	0.678	940	657	170	**3.85**
	SA-1430	L	0.20	0.55	0.571	958	670	506	**1.32**
Oconee-2	WF-25	C	0.35	0.68	0.745	774	541	170	**3.19**
Oconee-3	WF-67	C	0.24	0.60	0.728	900	629	170	**3.70**
TMI-1	WF-25	C	0.35	0.68	0.700	776	543	170	**3.20**
	SA-1526	L	0.35	0.68	0.655	779	545	502	**1.09**
CR3	WF-70	C	0.32*	0.58*	0.912*	764	534	169	**3.16**
	WF-8, 18	L	0.19*	0.57*	0.842*	946	661	506	**1.31**
ANO-1	WF-182-1	C	0.24	0.63	0.711	901	630	170	**3.69**
	WF-112	C	0.31	0.59	0.773	815	570	170	**3.34**
	WF-18	L	0.20	0.55	0.582	958	669	506	**1.32**

* Data are for 60 years (54 EFPY)

Figure 5-1 Demonstration of Flaw Stability under Level A and B Service Loadings



6. EVALUATION FOR LEVEL C AND D SERVICE LOADINGS

This section presents the calculations showing that the weld materials satisfy the acceptance criteria of Sections 2.1.2 and 2.1.3.

The method followed here consists of finding the limiting weld, then calculating the K_I applied to that weld during each of the Level C and D transients to find the limiting transient. For the limiting weld/transient combination, the effect of cladding is added and the plastic zone correction is performed. This allows calculation of the applied J-integral and, hence, comparison with the appropriate acceptance criteria.

Note that the acceptance criterion requires that the depth of the flaw for these conditions be one tenth of the base metal thickness plus the cladding thickness, but not to exceed 1.0 inch.

6.1 Limiting Weld

Under Level A and B Service Loadings, the limiting weld was determined to be the TMI-1 SA-1526 weld by comparing the ratio of the J-integral resistance to the applied J-integral for a T/4 flaw (See Table 5-3).

A similar set of data was created using a flaw size of T/10 and the fluence at a depth of T/10 (All fluence values are for 48 EFPY). This data appears in Table 6-1 and shows that the limiting weld for Level C and D Service Loads is, as it was for the Level A and B Service Loads, the TMI-1 SA-1526 weld. This weld is selected for the subsequent analysis.

6.2 Limiting Level C and D Service Loading

To perform a bounding analysis, the limiting weld found in Section 6.1 was analyzed for all appropriate Level C and D transients. The transients considered are those that subject the reactor vessel to the greatest thermal loads. The analyzed transients include the following:

Level C:	Stuck Open Turbine Bypass Valve (SOTBV)
Level D:	Design Basis Steam Line Break (DB-SLB)
	ANO-1 Steam Line Break (ANO-1 SLB)
	Core Flood Line Break (CFLB)
	Hot Leg Loss of Coolant Accident (HL-LOCA)

Figures 6-1 and 6-2 show all transients except the CFLB, which is shown in Figures 6-3 and 6-4. The CFLB is shown separately because the duration of that transient is much longer than the others. Pressure and temperature are assumed to hold steady at their final values, and are held constant until the thermal gradient through the shell has developed fully and begins to dissipate.

For the analysis of each transient, the crack tip temperature and, subsequently, the applied K_I are calculated as functions of time. The applied K_I can be shown as a function of crack tip temperature and plotted along with K_{Ic} and K_{Jc} versus temperature. This allows the critical transient and critical time in that transient to be easily identified. The program PCRIT 6.0 was used to calculate the crack tip temperature and the applied K_I.

The PCRIT output consists of the various components of applied K_I (thermal, pressure, residual, and the sum of these three) and the crack tip temperature, T, during each of the Level C and D transients. The applied K_I versus T plot appears as Figure 6-5, which also shows K_{Ic}, K_{Jc}, and lower bounding K_{Jc}.

The curve for K_{Jc} is based on the following equation.

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

where J_d is calculated as described in Section 3.1, at a constant flaw extension of 0.10 inch and a flaw depth (which affects the fluence level) of T/10. K_{Jc}(lower bound) is found by substituting J_d(lower bound) for J_d. E and ν are taken to be constant at 27,450 ksi and 0.3 respectively.

The ASME Code fracture toughness curve, K_{Ic} is given by the following equation.

$$K_{Ic} = 33.2 + 2.806\, e^{0.02(T-RT_{NDT}+100)},\ \text{ksi}\ \sqrt{\text{in}}$$

RT_{NDT} at the T/10 location of the reactor vessel is 282.7°F (based on initial RT_{NDT} of -7° per Reference 12). The values of K_{Ic} and K_{Jc} are tabulated in Table 6-2 and Table 6-3, respectively.

The Hot Leg Break LOCA transient is limiting since it most closely approaches the K_{Jc} limit of the weld. All subsequent calculations will apply to this transient. Furthermore, the time at which the applied J-integral most closely approaches K_{Jc} is 5.0 minutes. Subsequent calculations will be performed assuming conditions of the RV at this point in the transient.

6.3 Cladding Effects Owing to Thermal Gradient Load

The PCRIT code has a built-in cladding model for temperature calculations, however, the cladding is not considered in the fracture mechanics evaluations. The effect of the differential thermal expansion of the cladding on the stress intensity factor will subsequently be referred to as K_{Iclad}. Using the principal of superposition, K_{Iclad} is conservatively added to the applied K_I for the limiting transient.

In Reference [2], a conservative K_{Iclad} value of 9.0 ksi$\sqrt{\text{in}}$ was derived and this is added to K_I at each point in the transient. K_{Iclad} is included in the calculation of the applied J-integral in Section 6.4.

6.4 Acceptance Criteria Assessment for Level C Service Loadings (Article K-2300)

There is only one Level C Service Loading transient (Stuck Open Turbine Bypass Valves) listed in the functional specification and this transient is less severe than the Hot Leg LOCA (a Level D transient), therefore, the Hot Leg LOCA transient can be used to conservatively demonstrate the adequacy for these criteria.

The first acceptance criterion for Level C transients states that the crack driving force, $J_{applied}(a)$, must be less than the material toughness, $J_{material}(\Delta a = 0.1)$. $J_{applied}$ is calculated for the postulated flaw (a = T/10) during the critical transient (Hot Leg LOCA at t = 5.0 min.) using a factor of safety of 1.0 on loading in the beltline region of the RV using the relationship

$$J_{applied}(a) = \frac{K_{Itotal}^2(a)}{E}(1 - \nu^2)$$

where E = 27,450 ksi and ν = 0.3

Figure 6-6 shows that at a flaw extension of 0.1 inch the applied J-integral is well below the corresponding lower bounding material J_R value, satisfying this criterion. The values of J_R and $J_{applied}$ are 545 and 241 lb/in respectively, yielding a margin of 2.26 over and above the margin of safety provided by Appendix K.

The second acceptance criterion for Level C transients is that flaw extension must be ductile and stable using a factor of safety of 1.0 on loading.

Figure 6-6 shows that the applied J intersects with the material J_R curve in the blunting stage of the curve meaning the intersection point is below the J_{Ic} level thus not even starting ductile tearing. Appendix K was developed based on the premise that 0.1 inch approximately corresponds to a J_{Ic} point. Since there is no crack extension, the crack is stable.

6.5 Acceptance Criteria Assessment for Level D Service Loadings (Article K-2400)

The acceptance criterion for Level D transients is that flaw extension must be ductile and stable using a factor of safety of 1.0 on loading. The difference between the Level C and Level D criteria is that the J-integral resistance versus flaw extension curve is required to be a conservative representation (lower bound curve) of the vessel material for Level C transients, while it is required to be a best estimate representation (mean curve) for Level D transients (Section 3.3 discusses the model used to calculated $J_{material}$).

In Figure 6-6, the crack stability was established in Section 6.4 against the lower bounding J_R curve, therefore, the same is true against the mean J_R curve for Level D transients.

The last criterion for Level D conditions deals with the stability of the remaining ligament and reads as follows:

> Article K-2400 (c) The extent of stable flaw extension shall be less than or equal to 75% of the vessel wall thickness, and the remaining ligament shall not be subject to tensile instability.

Since there is no significant flaw extension, the ligament tensile stability is assured.

Table 6-1 J-Integral Resistance at a Flaw Depth of T/10

Plant	Limiting Welds		Fluence x 10^{-19} (n/cm^2)		$J_{0.1}$ at $T/_{10}$ (lb/in)		Comparison	
	Weld Identification	Weld Orient	at IS	at $^T/_{10}$	Mean	Lower Bound	J_1 (lb/in)	$J_{0.1}/J_1$
Oconee-1	SA-1229	C	1.11	0.906	867	606	66	**9.25**
	SA-1585	C	1.21	0.988	927	648	66	**9.90**
	SA-1430	L	1.02	0.833	946	661	164	**4.02**
Oconee-2	WF-25	C	1.33	1.086	756	528	65	**8.10**
Oconee-3	WF-67	C	1.30	1.062	886	619	65	**9.48**
TMI-1	WF-25	C	1.25	1.021	759	531	65	**8.14**
	SA-1526	L	1.17	0.955	762	533	163	**3.26**
CR3	WF-70	C	1.56*	1.27*	749	523	65	**8.05**
	WF-8, 18	L	1.44*	1.18*	935	653	165	**3.96**
ANO-1	WF-182-1	C	1.27	1.037	887	620	66	**9.46**
	WF-112	C	1.38	1.127	799	559	66	**8.53**
	WF-18	L	1.04	0.849	946	661	164	**4.02**

* Fluence Projections are for 60 years (54 EFPY)

Table 6-2 K_{Ic} for SA-1526 Weld Material

T-RT$_{NDT}$ (°F)	**K_{Ic} (ksi√in)**
50	89.6
60	102.0
70	117.3
80	135.9
90	158.6
100	186.4
110	220.3

Table 6-3 J_d and K_{Jc} for SA-1526 Weld Material

T (°F)	**J_d (lb/in)**		**K_{Jc} (ksi√in)**	
	Mean	**Lower bound**	**Mean**	**Lower bound**
300	1001	700	173.8	145.3
350	949	663	169.2	141.5
400	900	629	164.8	137.8
450	853	596	160.4	134.1
500	809	565	156.2	130.6
550	767	536	152.1	127.2
600	727	508	148.1	123.8

Figure 6-1 Level C and D Transients (Except CFLB) - RC Temperature vs. Time

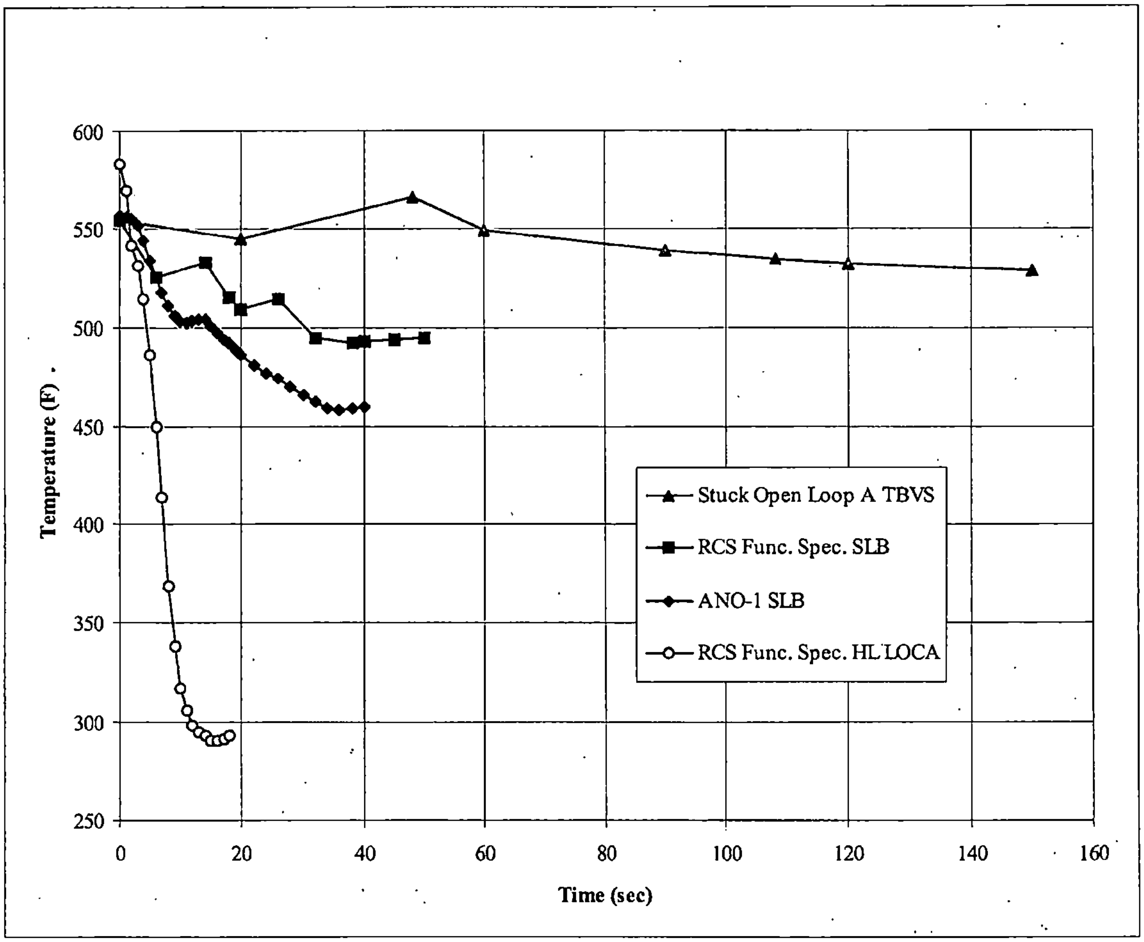


Figure 6-2 Level C and D Transients (Except CFLB) - RC Pressure vs. Time

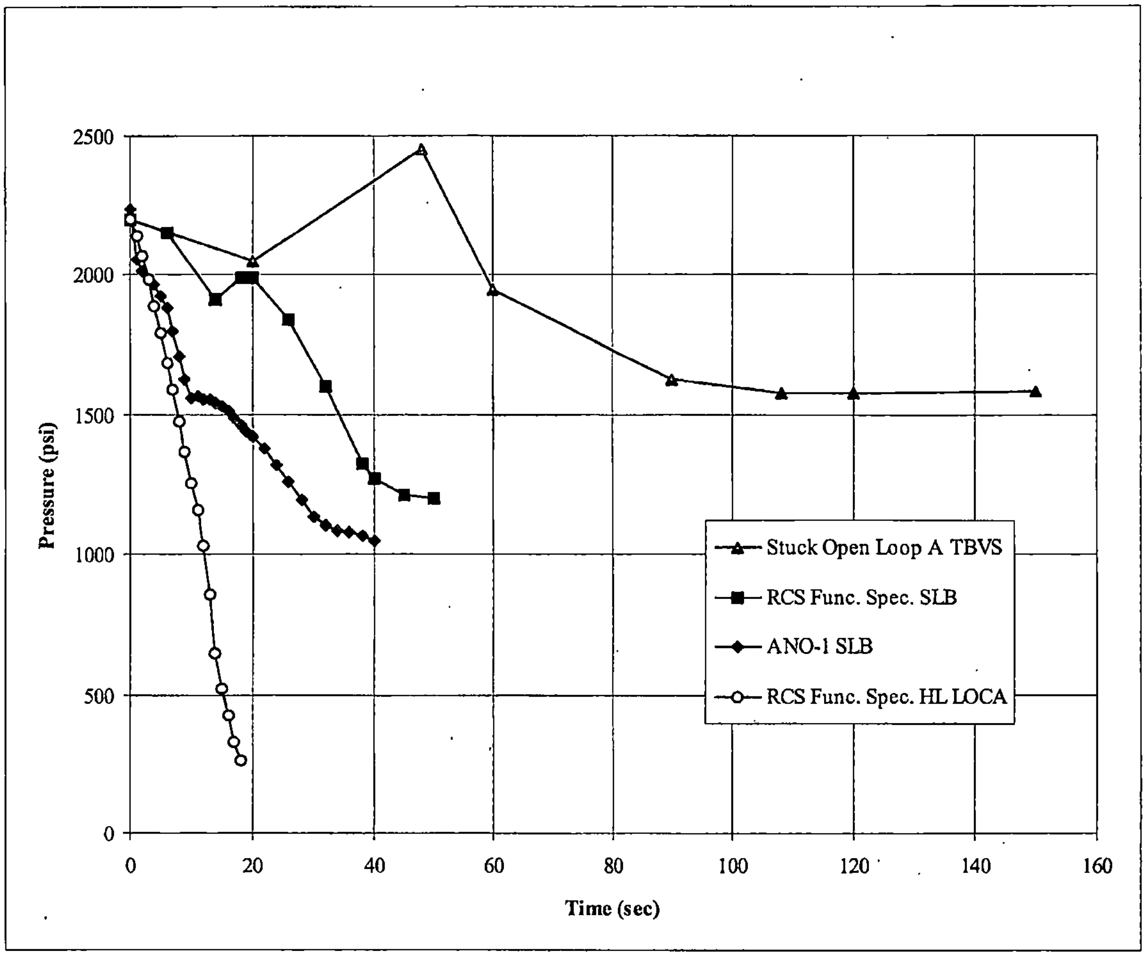


Figure 6-3 Core Flood Line Break RC Temperature vs. Time

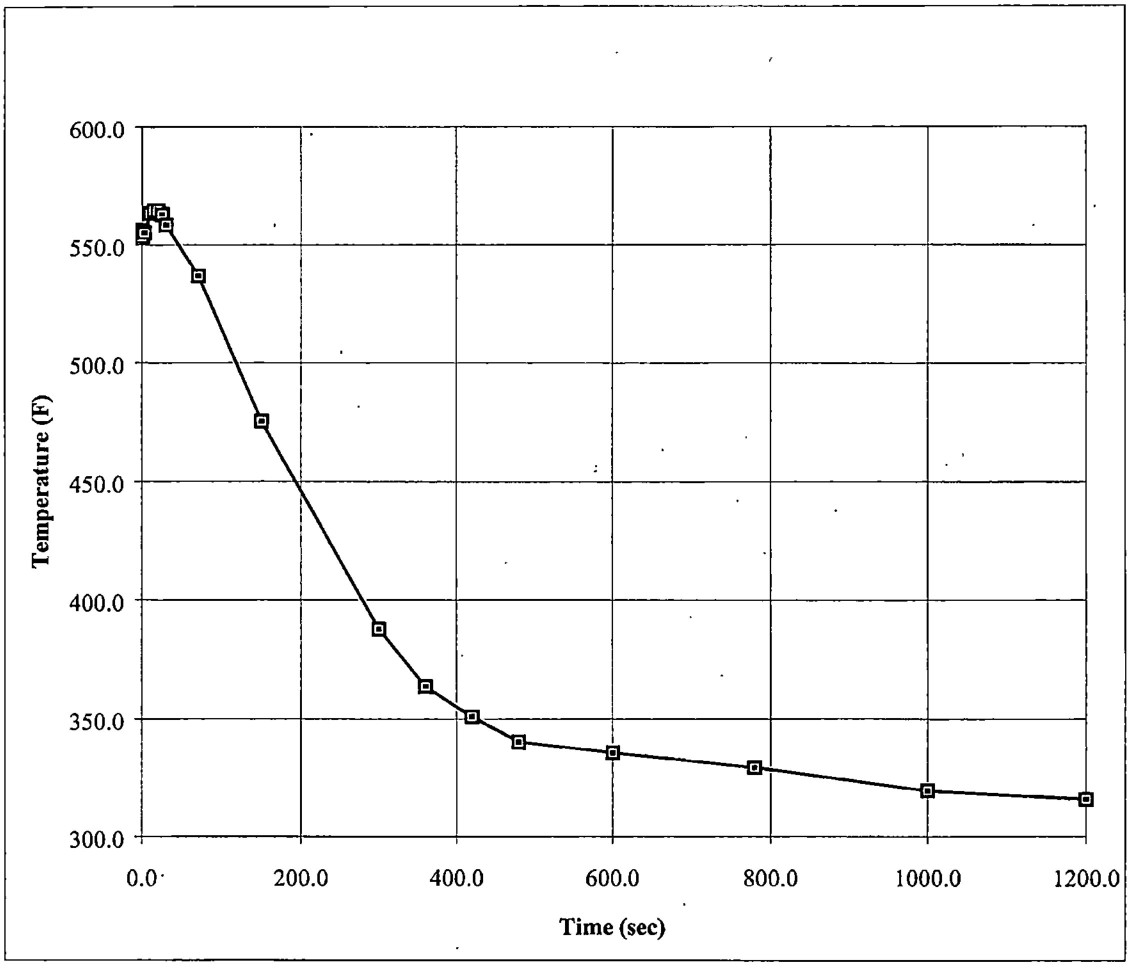


Figure 6-4 Core Flood Line Break RC Pressure vs. Time

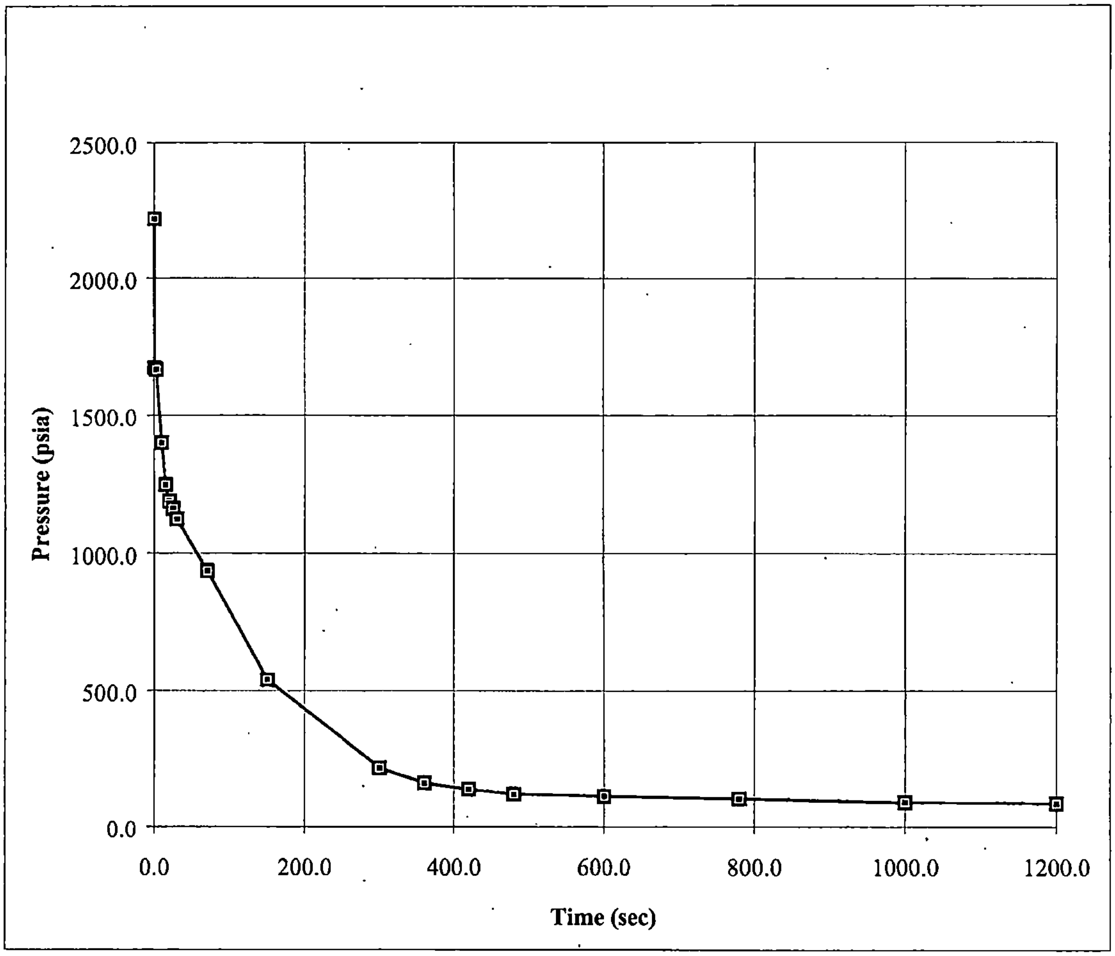


Figure 6-5 K_{Ic}, K_{Jc}, (Mean & Lower bound), and $K_{applied}$ for All Five Level C & D Transients

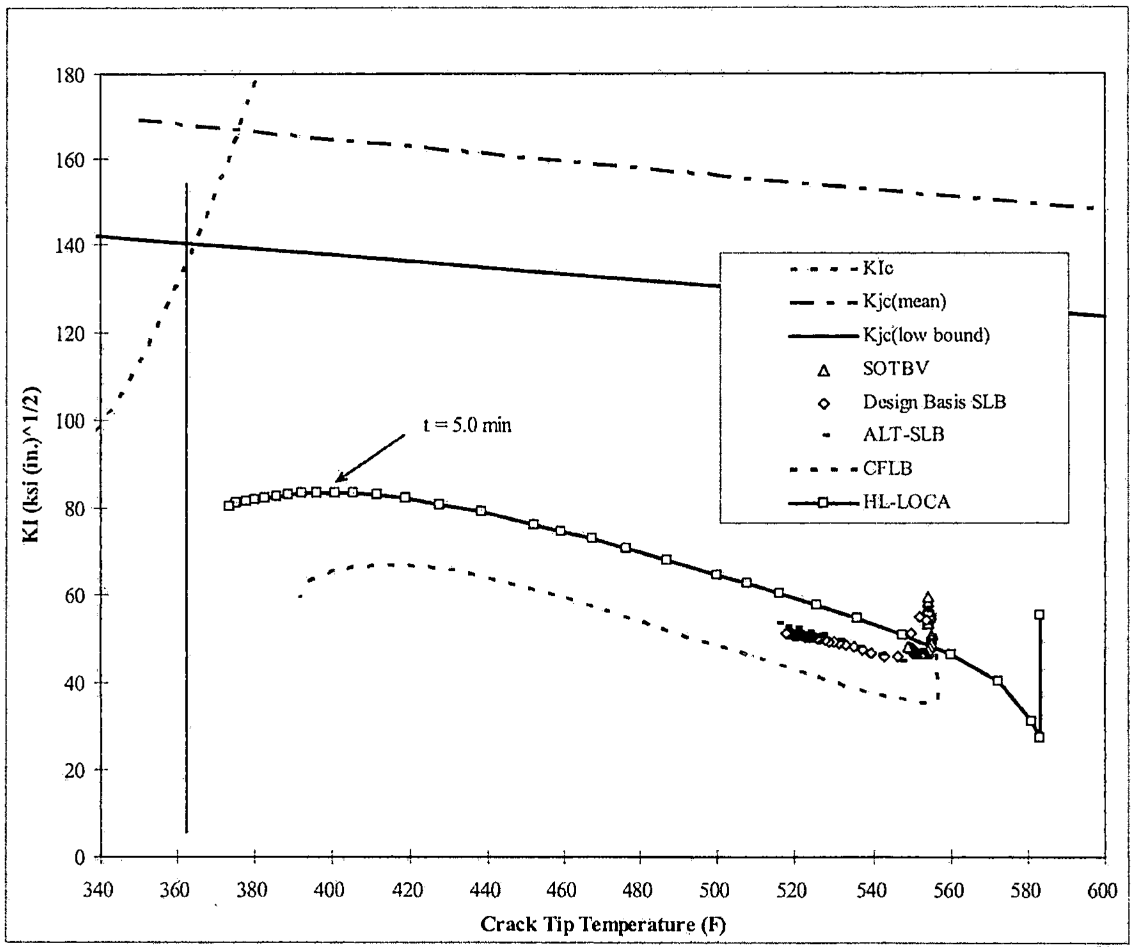
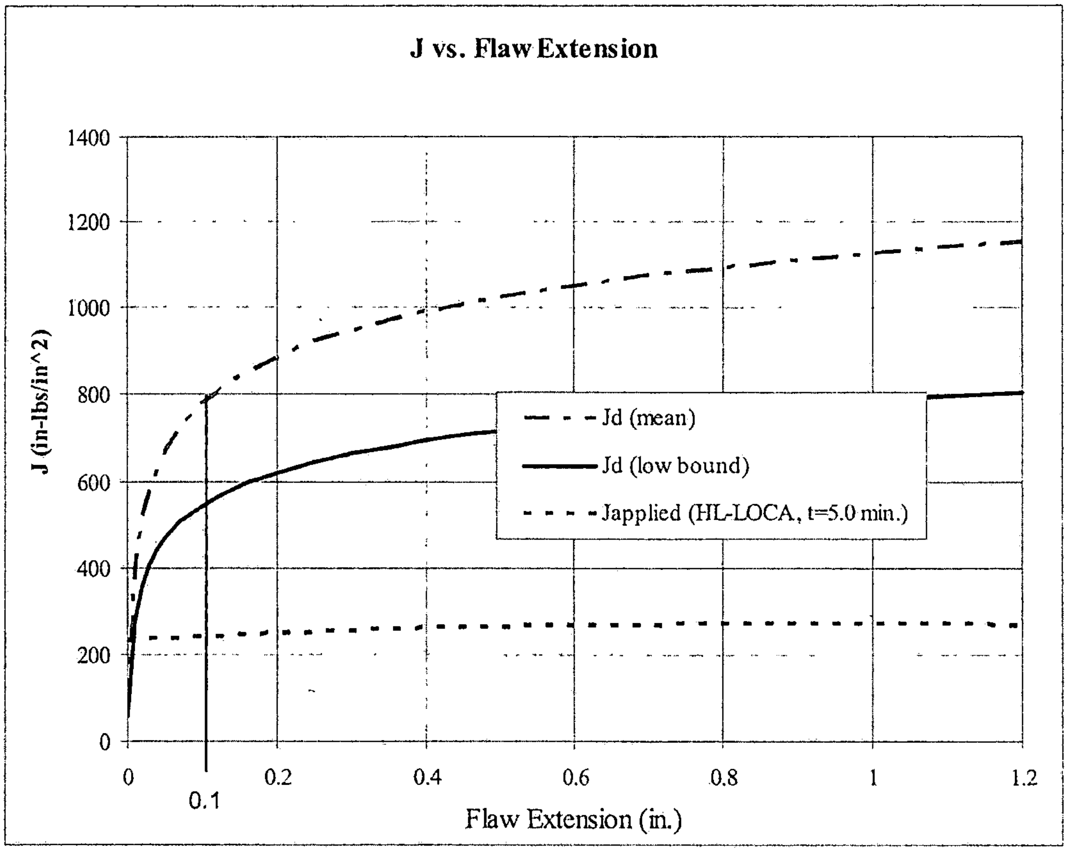


Figure 6-6 J vs. Flaw Extension Demonstrating Acceptability for Level C & D Service Loads



7. RECONCILIATION OF 54 EFPY FLUENCE

The projected fluence values at 60 years (54 EFPY) were compared to those at 48 EFPY. It was found that 54 EFPY fluence exceeds the 48 EFPY fluence for all reactor vessel locations with exception of the RV nozzles and RV closure flange. The CR3 beltline materials include the nozzle belt forging-lower, the circumferential weld that connects the nozzle belt forging-lower to the upper shell plate, upper shell consisting of two upper shell plates and two upper shell axial welds, the circumferential weld that connects the upper shell to the lower shell, and the lower shell consisting of two lower shell plates and two lower shell axial welds. All RV vessel nozzles were found to receive fluences less than 1.0E17 n/cm^2 at 54 EFPY and are not considered belt line material. The upper shelf energy values for all plates and forgings remain above 50 foot-pounds at 60 years (54 EFPY). Results of equivalent margins analyses for the reactor vessel welds, shown in Tables 7-1 and 7-2 below, demonstrate that the CR3 welds remain acceptable at 60 years (54 EFPY). These tables show that the material J-integrals for the CR3 welds at 60 years (54 EFPY) are bounded by the values at 48 EFPY for the limiting weld at TMI-1.

Table 7-1 Comparison of J-Integral Resistance at a Flaw Depth of 1/4T at 48 and 54 EFPY

Beltline Weld ID	Surface Fluence x 10^{-19} (n/cm^2)	Fluence at T/4 x 10^{-19} (n/cm^2)	$J_{0.1}$ material lower bound (in-lb/in^2)	J_1 applied (in-lb/in^2)	$\frac{J_{0.1}}{J_1}$
At 48 EFPY					
WF-70	N/A	0.672	544	169	**3.21**
WF-8, 18	N/A	0.650	667	506	**1.32**
At 60 years (54 EFPY)					
WF-70	N/A	0.912	534	169	**3.16**
WF-8, 18	N/A	0.842	661	506	**1.31**

Table 7-2 Comparison of J-Integral Resistance at a Flaw Depth of T/10 at 48 and 54 EFPY

Beltline Weld ID	Surface Fluence x 10^{-19} (n/cm^2)	Fluence at T/10 x 10^{-19} (n/cm^2)	$J_{0.1}$ material lower bound (in-lb/in^2)	J_1 applied (in-lb/in^2)	$\frac{J_{0.1}}{J_1}$
At 48 EFPY					
WF-70	1.20	0.980	532	65	**8.14**
WF-8, 18	1.16	0.947	658	165	**3.99**
At 60 years (54 EFPY)					
WF-70	1.56	1.27	523	65	**8.05**
WF-8, 18	1.44	1.18	653	165	**3.96**

8. SUMMARY AND CONCLUSIONS

Limiting Weld:

The limiting weld for both the A and B and the C and D analyses is the TMI-1 SA-1526 weld.

Limiting Transient:

Cooldown at a rate of 100 °F/hour is the only transient considered for A and B Service Loads. The limiting transient for the analysis of C and D Service Loads is the Hot Leg Loss of Coolant Accident.

Acceptance Criteria for A and B Service Loads:

The acceptance criteria are satisfied because

1) with a factor of safety on pressure of 1.15 the ratio of material J-integral to applied J-integral at a flaw extension of 0.1 inch is greater than unity for the limiting weld, and
2) with a factor of safety on pressure of 1.25 the slope of the applied J-integral vs. flaw extension curve is less than the material J-integral vs. flaw extension curve at their point of intersection for the limiting weld.

Acceptance Criteria for C and D Service Loads:

The acceptance criteria are satisfied because

1) with a factor of safety of 1.0 on pressure, the ratio of material J-integral to applied J-integral at a flaw extension of 0.1 inch is greater than unity for the limiting weld; and
2) with a factor of safety on pressure of 1.0, the slope of the applied J-integral vs. flaw extension curve is less than the material J-integral vs. flaw extension curve at their point of intersection for the limiting weld; and
3) the extent of stable flaw growth is less than 75% of the vessel wall thickness and the remaining ligament is not subject to tensile instability.

Conclusions:

The analysis of this document demonstrates that the welds of the CR3 reactor vessel satisfy the acceptance criteria of Appendix K of Section XI of the ASME Code and, therefore, provide margins of safety equivalent to those of Appendix G of Section XI. The equivalent margins analysis has shown that the Crystal River Unit 3 reactor vessel welds at 54 EFPY are bounded by the limiting weld at Three Mile Island Unit 1 at 48 EFPY. It can therefore be concluded that the CR3 reactor vessel welds have adequate upper-shelf toughness and satisfy the requirement of Appendix G to 10 CFR 50 at 54 EFPY.

9. CERTIFICATION

This report is an accurate description of the low upper-shelf toughness fracture analysis of the Crystal River Unit 3 reactor vessel.

SJ Noronha 8|25|09

Silvester J. Noronha, Engineer IV — Date
Structural and Fracture Mechanics Unit

This report has been reviewed and is an accurate description of low upper-shelf toughness fracture analysis of the Crystal River Unit 3 reactor vessel.

D E Killian 8/25/09

Douglas E. Killian, Advisory Engineer — Date
Structural and Fracture Mechanics Unit

Verification of independent review.

T.M. Wiger 8/25/09

Tim M. Wiger, Manager — Date
Structural and Fracture Mechanics Unit

This Report is approved for release.

Mark A. Rinckel 8/25/09

Mark A. Rinckel, Project Manager — Date

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[1]Available from AREVA NP Inc, Lynchburg, VA