GE Nuclear Energy

ENGINEERING & TECHNOLOGY
GE Nuclear Energy
175 Curtner Avenue, San Jose, CA 95125

GE-NE-0000-0027-0575-01, Rev. 0
e-DRF No. 0027-0575
Class I
March 2004

THE UPPER SHELF ENERGY EVALUATION FOR RPV ELECTROSLAG WELDS AT QUAD CITIES UNIT 2

March 2004

Prepared for

Exelon Corp.
Quad Cities Unit 2

Final Report, Rev. 0

GENE-0000-0027-0575-01
e-DRF No. 0027-0575

THE UPPER SHELF ENERGY EVALUATION FOR RPV ELECTROSLAG WELDS AT QUAD CITIES UNIT 2

March 2004

Prepared by: ____________________
H.S. Mehta, Engineering Fellow, Fracture Mechanics
Structural Analysis & Hardware Design

Verified by: ____________________
D.V. Sommerville, Engineer
Structural Analysis & Hardware Design

Approved by: ____________________ 3/31/04
for M.R. Schrag, Manager A. MAHADEVAN
Structural Analysis & Hardware Design

DISCLAIMER OF RESPONSIBILITY
Important Notice Regarding the Contents of this Report
Please Read Carefully

Table of Contents

List of Tables

Table **Page No.**

List of Figures

Figure **Page No.**

1. EXECUTIVE SUMMARY

10CFR50 Appendix G states that the reactor pressure vessel (RPV) must maintain upper shelf energy (USE) throughout its life 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 USE will provide margins of safety against fracture equivalent to those required by Appendix G of Section XI the ASME Code. BWR Owners' Group (BWROG) developed a licensing topical report on equivalent margin analysis for low USE BWR/2 through BWR/6 RPVs, which was reviewed and approved by the NRC for use by individual utilities.

BWRVIP-74 provided a statistical treatment of the initial USE for a variety of base and weld metals used in BWR RPV fabrication. The report provided lower bound (i.e., mean minus κ standard deviation) USE values for use in cases where the initial USE values may not be available or may have inadequate pedigree.

At Quad Cities, Unit 2 (QC-2), the plant assumed a lower bound USE for the electroslag welds based on BWRVIP-74. When the larger than expected measured USE reduction in one of the irradiated specimen was taken into account using the guidance provided in position 2.2 of Regulatory Guide 1.99, Revision 2, the predicted end of life (EOL) USE value (34.2 ft-lb) didn't meet the minimum required value of 35 ft-lb stated in the topical report. This report documents a plant-specific evaluation that was conducted to show compliance with the USE requirements.

This QC-2 electroslag weld USE evaluation followed essentially the methodology outlined in the topical report. The applied J-integral calculation formulas and the material J-R curves for various operating conditions were consistent with the guidelines provided in the ASME Code Case N-512-1, Appendix K of ASME Section XI and the Regulatory Guide 1.161. The evaluation showed that the Level B Condition was the governing one. The ductile crack growth stability requirement showed that an USE of 32.4 ft-lb satisfies the criteria compared to the predicted EOL value of 34.2 ft-lb.

Based on the results of this plant-specific evaluation, it is concluded that the electroslag welds in QC-2 RPV meet the margins of safety against fracture equivalent to those required by Appendix G of Section XI the ASME Code. This conclusion is also valid for the extended power uprate (EPU) operation.

2. INTRODUCTION AND BACKGROUND

The nuclear RPVs are typically made of low-alloy ferritic steels (e.g., SA302B; or SA533, Grade B, Class 1). They are exposed to high energy neutrons in the beltline region; as a result of the constituent parts (i.e., the plates, forgings, and welds) can experience degradation of material properties: yield and ultimate tensile strengths increase, brittle-to-ductile transition temperature increases, and the upper shelf toughness decreases. The last two effects are the most important from the point of view of structural margins during operation of a RPV. The impact of low Charpy USE on the QC-2 RPV integrity analyses is the subject of this report.

10CFR50 Appendix G [1] states that the RPV must maintain USE throughout its life 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 USE will provide margins of safety against fracture equivalent to those required by Appendix G of Section XI the ASME Code [2]. In September 1992, the Nuclear Regulatory Commission (NRC), in discussing the preliminary review of the responses to Generic Letter 92-01, strongly recommended the equivalent margin analyses be done by the Owners' Groups. In response to this BWROG developed a licensing topical report on equivalent margin analysis for low USE BWR/2 through BWR/6 vessels [3] that was reviewed and approved by the NRC [4]. The topical report, which could be referenced by utilities as part of their licensing basis, can be used to address compliance with the 50 ft-lb requirement. Appendix B of the topical report presents the steps required to show that the USE requirements presented in the report can be applied to individual BWR plants. The plants always have the option to perform a plant-specific USE margin evaluation.

The topical report followed the methods provided in the then-draft Appendix X of the ASME Code, which has since become Code Case N-512 [5] and subsequently revised as Code Case N-512-1 [6]. This Code Case was incorporated in the Section XI Code as Non-Mandatory Appendix K [7]. The NRC staff reviewed the analysis methods in Appendix K and found them to be technically acceptable but not complete with respect to information on the selection of transients, and the selection of material properties. As a result the NRC issued Regulatory Guide 1.161 [8] providing specific guidance on these issues.

BWRVIP-74 [9] provided a statistical treatment of the initial USE for a variety of base and weld metals used in BWR RPV fabrication. The report provided lower bound (i.e., mean minus κ standard deviation) USE values for use in cases where the initial USE values may not be available or may have inadequate pedigree.

At QC-2, the plant assumed a lower bound USE for the electroslag welds based on BWRVIP-74. When the larger than expected measured USE reduction in one of the irradiated specimen was taken into account using the guidance provided in position 2.2 of Regulatory Guide 1.99, Revision 2 [10], the predicted USE value didn't meet the minimum required value of 35 ft-lb stated in the topical report. Therefore, a plant-specific evaluation was conducted to show compliance.

The evaluation essentially followed the methodology outlined in the topical report. Special care was taken to assure that the applied J-integral calculation formulas and the material J-R curve equations were consistent with the requirements of Section XI Code Case 512-1, Appendix K and the Regulatory Guide 1.161. Also, the selection of transients was justified in relation to QC-2 vessel transients for Levels A through D operating conditions.

3. QUAD CITIES 2 RPV DATA & ELECTROSLAG USE

The QC-2 vessel geometry information is provided in Reference 11. The vessel radius, R, in the beltline region is 125.7 inches. The nominal wall thickness, t, is 6.13 inches excluding the cladding. The nominal clad thickness, t_c, is 0.19 inch.

The design pressure of the RPV is 1250 psi. The design pressure remained unchanged with the introduction of EPU. The Selection of appropriate transients for various operating conditions is discussed in the later sections.

The electroslag weld specimen in the second capsule at QC-2 showed a USE drop of 27.6% with a fluence level of 6.6×10^{16} n/cm^2 compared to the predicted drop of 8.8% using Reference 10. It is well known that the USE drop at fluence levels less than 1×10^{17} n/cm^2 shows considerable scatter. This is supported by the data from the Dresden and Quad Cities capsule data. Nevertheless, this bounding data was used to predict the end of life (EOL) USE drop for QC-2. Therefore, using the guidance outlined in position 2.2 of Reference 9, the predicted drop at EOL fluence of 3.9×10^{17} n/cm^2 was calculated as 42.7%. Consistent with GE practice, this was rounded up to 43%. Reference 9 (Figure B-6) shows the unirradiated mean minus κ sigma USE value for electroslag welds as 60 ft-lb. Applying a 43% reduction to this value gives a predicted EOL USE value of [60x(100-43)/100] or 34.2 ft-lb. Reference 3 and 9 give the lowest acceptable value of USE for electroslag welds as 35 ft-lbs. Since the predicted value of 34.2 ft-lbs is slightly below the allowable value in References 3 and 9, a plant-specific evaluation was conducted to show compliance as described in the next sections. The J-R curves used in the evaluation are based on the USE value of 34.2 ft-lb.

4. USE MARGIN EVALUATION METHODOLOGY

The USE margin evaluation methodology used in this report is consistent with that prescribed in References 6 through 8. Although the References 5 through 7 were in development at the same time as the topical report [3] was being developed and Reference 8 was published later, a review of the methodology used in Reference 3 indicated that in almost all respects it is consistent with References 6 through 8. If there were any small differences, such as that in the selection of J-R curves, the topical report used a conservative approach. The methodology prescribed in Reference 8 is exclusively followed in this report.

The acceptance criteria and the equations for the calculation of J applied values are described in this section. The selection of appropriate J-R curves is described in the next section.

4.1. Acceptance Criteria

The acceptance criteria for Level A and B conditions are described in Section 1.1 (Equations 1 and 2) of Reference 8:

$$J_{applied} < J_{0.1} \quad (1)$$

$$\partial J_{applied}/\partial a < \partial J_{material}/\partial a, \text{ with load held constant at } J_{applied} = J_{material} \quad (2)$$

The second equation assures stability under ductile crack growth. Figure 1 illustrates this concept. Both the circumferential and axial flaws are postulated. The postulated flaws for all operating conditions are semi-elliptical surface flaws with an aspect ratio of 6-to-1 surface length to flaw depth. The assumed crack depth is one-fourth the base metal wall thickness.

For the Level C conditions, the acceptance criteria are those given in Section 1.2 (Equations 3 and 4) of Reference 8. These are essentially the same as the preceding Equations (1) and (2). However, the postulated flaw depth is one-tenth the base metal wall thickness, plus the clad thickness, but with total depth not to exceed 1.0 inch. The safety factor for applied pressure loading is 1.0.

For the Level D conditions, the acceptance criteria are those given in Section 1.3 (Equation 5) of Reference 8. Only the ductile crack growth stability is evaluated. The postulated flaw depth is the same as that for Level C conditions. The material J-Integral resistance curve is based on best estimate. The safety factor on applied loading is 1.0.

4.2. Calculation of Applied J-Integral

The calculation of applied J-Integral consists of three steps: Step 1 is to calculate the K values from pressure and heatup/cooldown loadings; Step 2 is to calculate the effective flaw depth which includes a plastic zone size correction; and Step 3 is to calculate the J-Integral for small-scale yielding based this effective flaw depth. The calculated K values are in the units of ksi$\sqrt{in}$.

<u>Internal Pressure Loading</u>

For an axial flaw with depth 'a' equal to (0.25t+0.1 in.), the stress intensity factor from internal pressure, p_a, with a safety factor, SF, on pressure equal to 1.15 using Equation (6) of Reference 8:

$$K_{Ip}^{Axial} = (SF)\, p_a\, [1 + (R_i/t)]\, (\pi a)^{0.5}\, F_1 \quad (3)$$

$$F_1 = 0.982 + 1.006\, (a/t)^2$$

For a circumferential flaw with depth 'a' equal to (0.25t+0.1 in.), the stress intensity factor from internal pressure, p_a, with a safety factor, SF, on pressure equal to 1.15 using Equation (7) of Reference 8:

$$K_{Ip}^{Circum.} = (SF)\, p_a\, [1 + \{R_i/(2t)\}]\, (\pi a)^{0.5}\, F_2 \quad (4)$$

$$F_2 = 0.885 + 0.233\, (a/t) + 0.345\, (a/t)^2$$

Heatup/Cooldown Loading

For an axial or circumferential flaw with depth 'a' equal to (0.25t+0.1 in.), the "steady state" (time independent) stress intensity factor from radial thermal gradients is obtained by using Equation (8) of Reference 8:

$$K_{It} = (CR/1000)\, t^{2.5}\, F_3 \quad (5)$$

$$F_3 = 0.69 + 3.127\, (a/t) - 7.435\, (a/t)^2 + 3.532\, (a/t)^3$$

The above equation for K_{It} is valid for $0 \leq CR \leq 100°F/hr$.

For the transients in which the heatup/cooldown rates are greater than 100°F/hr, Reference 3 used finite element analysis to determine the stress distribution through the RPV wall and the K values were then calculated using the Raju-Newman method [12].

Effective Flaw Depth

The effective flaw depth for small-scale yielding, a_e, was based on Equation (9) of Reference 8:

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

Consistent with the topical report [3], the value for σ_y was assumed as 69 ksi.

J-Integral Calculation

The J-integral from the K values was calculated using Equation (10) of Reference 8:

$$J_{applied} = 1000\,(K'_{Ip} + K'_{It})^2/E'$$

Where, the K' values are stress intensity factors based on effective flaw depth and E' is $E/(1-\nu^2)$. The value of ν was taken as 0.3 and consistent with Reference 3, the value of E was assumed as 27700 ksi. The units of J are in-lb/in^2.

5. SELECTION OF MATERIAL J-R CURVES

The generic J-Integral fracture resistance curve equation is given as Equation (17) in Reference 8:

$$J_R = (MF)\,\{C1\,(\Delta a)^{C2} \exp\,[C3\,(\Delta a)^{C4}]\} \quad (6)$$

For electroslag welds, Section 3.2 (generic Reactor Pressure Welds) of Reference 8 provides the values of various constants in the preceding equation. For analyses addressing Service Levels A, B, and C, the factor MF was set as 0.629. For analyses addressing Service Level D, the value of MF was set as 1.0. The mathematical expressions for other constants are given by Equations (22) through (25) of Reference 8:

$$C1 = \exp\,[-4.12 + 1.49 \ln(CVN) - 0.00249T] \quad (7)$$
$$C2 = 0.077 + 0.116 \ln C1 \quad (8)$$
$$C3 = -0.0812 - 0.0092 \ln C1 \quad (9)$$
$$C4 = -0.5 \quad (10)$$

The term 'CVN' is the Charpy USE. As indicated in Section 3, the conservatively predicted EOL Charpy USE for the QC-2 electroslag welds is 34.2 ft-lb. This value was used in calculating the value of constant C1. The normal operating temperature for region B (that contains the beltline region) of the vessel is specified as 546°F [13]. Therefore, this value was conservatively used in calculating the value of constant C1.

The calculated J-Integral resistance curves for the various operating conditions are shown in Figure 2.

6. EVALUATION LEVEL A & B CONDITIONS

Key steps in this evaluation are the calculation of applied J-integral and the flaw stability evaluation. The impact of EPU operation is also discussed.

6.1. Level A and B Service Loadings

The two loadings to be considered are internal pressure and thermal heatup/cooldown rates. The Level A and B heatup/cooldown rates for QC-2 RPV are specified in the associated reactor thermal cycle diagram [13]. The topical report [3] also analyzed an additional transient identified as loss of feedwater pumps that is specified for BWR/6 standard plants in their RPV thermal cycle drawing [15]. However, the analysis in the topical report showed that the 100°F/hr case was still bounding compared to this transient. The difference between the RPV geometry considered in the topical report (R= 126.7 in. and t= 6.19 in.) and the QC-2 RPV geometry (R=125.7 in. and t= 6.13 in.) is less than 1% and thus was considered insignificant in terms of the calculated thermal transient stress. Thus, the conclusion reached in the topical report was also determined to be valid for the QC-2 case and therefore, only the 100°F/hr case was considered in this evaluation.

The specified design pressure for QC-2 RPV is 1250 psi. Consistent with the approved topical report [3], the accumulation pressure is 1.1 times the design pressure and is, thus, equal to 1375 psi. The internal pressure value used in the $J_{0.1}$ criterion is 1.15 times the accumulation pressure (i.e., 1375x1.15 or 1581 psi). Similarly, the internal pressure value used in the flaw stability criterion is 1.25 times the accumulation pressure or 1719 psi.

The QC-2 RPV wall thickness in the beltline region is 6.13 in. Therefore, the postulated 1/4t flaw has a depth of (6.13x0.25) or 1.53 in.

6.2. Level A and B Conditions Evaluation

Table 1 shows the calculated values of applied J-integral for 1.15 accumulation pressure at several crack depths beginning with the 1/4t depth. The calculations for the axial flaw are shown first followed by the circumferential flaw. For the $J_{0.1}$ criterion, the applied J-integral values at a = 1.63 inch are relevant. A review of Table 1 indicates that the applied J-integral values for the axial flaw case bound those for the circumferential flaw case. Therefore, the $J_{0.1}$ criterion check was conducted only for the axial flaw case. Figure 3 shows a comparison between the calculated applied J-integral value for the axial flaw and the electroslag weld J-R curve. It is seen that the $J_{0.1}$ criterion is satisfied for the limiting case of axial flaw.

Table 2 shows the calculated values of applied J-integral for 1.25 accumulation pressure at several crack depths beginning with 1/t depth. The calculations are shown for both the axial and the circumferential flaws. However, a review of Table 2 indicates that the axial flaw case is governing. Figure 4 shows the plot of applied J-integral curve and the electroslag weld J-R curve. Flaw stability at a given applied load is assured when the slope of the applied J-integral curve is less than the slope of the material J-R curve at the point on the J-R curve where the two curves intersect (see Figure 1). It is seen that the stability criterion is satisfied with the assumed EOL USE of 34.2 ft-lb for the QC-2 electroslag welds.

To further assess the margin, the CVN USE energy level was reduced till the slope of the electroslag material J-R curve equaled the slope of the J applied curve. The results are shown in Figure 5. It is seen that this occurs at a CVN USE level of 32.43 ft-lb. At this CVN level, the slope of the J applied curve ($\partial J_{applied}/\partial a$) equals the slope of the material J-R curve ($\partial J_{material}/\partial a$). Thus, the difference between the conservatively estimated EOL USE of 34.2 ft-lb and 32.43 ft-lb is the indication of the margin.

6.3. Impact of EPU Operation

Reference 13 shows the thermal cycle drawing for QC-2 RPV. The impact of EPU on the RPV thermal cycle parameters is discussed in Reference 14. A review of the equivalent margins calculated in this section (Level A and B) and those in the next section (Level C and D) indicates that the Level B condition is governing. For the governing Level B evaluation, the key parameters are the design pressure and the operating temperature. According to Reference 14, the design pressure remains unchanged due to EPU and the operating temperature changes from 346°F to 347°F. The 1°F temperature change causes negligible change in the Level B condition material J-R curve and the calculated transient temperature stresses.

For the non-governing Level B case such as the loss of feedwater pumps transient, operating pressures rather than design pressure are used in the evaluation. However, the changes in the operating pressures for this case are less than 0.5% due to EPU and were thus considered insignificant.

Therefore, it is concluded that the margins calculated in this section remain also valid for EPU operation.

7. EVALUATION LEVEL C & D CONDITIONS

The postulated flaw depth for the evaluation of Level C and D loadings is one-tenth the base metal wall thickness, plus the clad thickness, but with total depth not to exceed 1.0 inch. The plate thickness in the beltline region is 6.13 in. The nominal thickness of the clad is 0.19 inch. Therefore, the postulated crack depth is (6.13x0.1 + 0.19) or 0.80 inch.

7.1. Level C Service Loadings

The QC-2 RPV thermal cycle drawing [13] does not specify Level C events. The topical report [3] used a RPV thermal cycle drawing to select a limiting Level C transient. The topical report [3] determined that for the BWR/3-6 product lines, the Improper Start of Cold Recirculation Loop transient (Transient 24 in Reference [15]) is the most limiting Level C transient. Figure 6 shows this transient. Since the geometry differences between the QC-2 RPV and the RPV geometry analyzed in the topical report [3] were minor (as discussed in Section 6.1), the K values for transient 24 calculated in the topical report were also used in this evaluation. This meant using the same K_t fit coefficients as shown in Table 6-1b of the topical report.

Section 6.1.3 of the topical report [3] discusses the calculation method for the K values due to cladding. The same technical approach and the clad stress were used in this report.

7.2. Level C Service Evaluation

Table 3 shows the calculated values of Level C condition applied J-integral for axial and circumferential flaws. Since the internal pressure didn't change during the thermal transient (see Figure 6), only one set of applied J-integral calculations (shown in Table 3) was performed to evaluate the $J_{0.1}$ and the flaw stability criteria. As expected the axial flaw case is governing. The material J-R curve for Level C condition is the same as that for the Level A and B conditions. The $J_{0.1}$ criterion and the flaw stability evaluations are graphically shown in Figures 7 and 8, respectively. It is seen that both the criteria are satisfied.

7.3. Level D Service Loadings

The limiting Level D transient is the pipe rupture condition (Transient or Event 27). The pressure temperature profile is shown in Figure 9. Since the geometry differences between the QC-2 RPV and the RPV geometry analyzed in the topical report [3] were minor (as discussed in Section 6.1), the K values for transient 27 calculated in the topical report were also used in this evaluation. Section 6.2.2 of the topical report describes the fracture mechanics methodology used in the derivation of the K values. The K_t fit coefficients shown in Table 6-2 of the topical report were therefore also used in this report.

7.4. Level D Service Evaluation

Table 4 shows the calculated values of Level D condition applied J-integral for axial and circumferential flaws. The internal pressure at the end of the transient was used in the applied J integral calculations. As expected the axial flaw case is governing. The material J-R curve for Level D condition is based on the margin factor (MF) of 1.0 as specified in Reference 8. Figure 10 graphically shows the flaw stability evaluation. It is seen that the ductile flaw crack growth stability criterion is satisfied.

8. SUMMARY AND CONCLUSIONS

10CFR50 Appendix G states that the RPV must maintain USE throughout its life 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 USE will provide margins of safety against fracture equivalent to those required by Appendix G of Section XI the ASME Code. BWROG developed a licensing topical report on equivalent margin analysis for low USE BWR/2 through BWR/6 RPVs, which was reviewed and approved by the NRC for use by individual utilities.

BWRVIP-74 provided a statistical treatment of the initial USE for a variety of base and weld metals used in BWR RPV fabrication. The report provided lower bound (i.e., mean minus κ standard deviation) USE values for use in cases where the initial USE values may not be available or may have inadequate pedigree.

At QC-2, the plant assumed a lower bound USE for the electroslag welds based on BWRVIP-74. When the larger than expected measured USE reduction in one of the irradiated specimen was taken into account using the guidance provided in position 2.2 of Regulatory Guide 1.99, Revision 2, the predicted EOL USE value (34.2 ft-lb) didn't meet the minimum required value of 35 ft-lb stated in the topical report. This report documents a plant-specific evaluation that was conducted to show compliance with the USE requirements.

This QC-2 electroslag weld USE evaluation followed essentially the methodology outlined in the topical report. The applied J-integral calculation formulas and the material J-R curves for various operating conditions were consistent with the guidelines provided in the ASME Code Case 512-1, Appendix K of ASME Section XI and the Regulatory Guide 1.161. The evaluation showed that the Level B Condition was the governing one. The ductile crack growth stability requirement showed that an USE of 32.4 ft-lb satisfies the criteria compared to the predicted EOL value of 34.2 ft-lb.

Based on the results of this plant-specific evaluation, it is concluded that the electroslag welds in QC-2 RPV meet the margins of safety against fracture equivalent to those required by Appendix G of Section XI the ASME Code. This conclusion is also valid for the EPU operation.

9. REFERENCES

[1] "Fracture Toughness Requirements," Appendix G to Part 50 of Title 10, the Code of Federal Regulations, July 1983.

[2] "Fracture Toughness Criteria for Protection Against Failure," Appendix G to Section XI of the ASME Boiler & Pressure Vessel Code, 1989 Edition.

[3] Mehta, H.S., et al., "10CFR50 Appendix G Equivalent Margin Analysis for Low Upper Shelf Energy in BWR/2 Through BWR/6 Vessels," NEDO-32205-A, Revision 1, February 1994.

[4] Safety Evaluation of Reference 3 by NRR, December 08, 1993.

[5] Code Case N-512, "Assessment of Reactor Vessels with Low Upper Shelf Charpy Impact Energy Levels," Section XI, Division 1 Code, February 12, 1993.

[6] Code Case N-512-1, "Assessment of Reactor Vessels with Low Upper Shelf Charpy Impact Energy Levels," Section XI, Division 1 Code, August 24, 1995.

[7] American Society of Mechanical Engineers, "Assessment of Reactor Vessels with Low Upper Shelf Charpy Impact Energy Levels," Appendix K, A93, pp. 482.1-482.15, Section XI, "Rules for Inservice Inspection of Nuclear Power Plant Components," 1992 Edition, 1993 Addenda, New York, December 1993.

[8] USNRC, "Evaluation of Reactor Pressure Vessels with Charpy Upper-Shelf Energy Less Than 50 Ft-lb," Regulatory Guide 1.161, June 1995.

[9] BWR Vessel and Internals Project, BWR Reactor Pressure Vessel Inspection and Flaw Evaluation Guidelines (BWRVIP-74), EPRI, Palo Alto, CA, and BWRVIP: 1999, TR-113596.

[10] USNRC, "Radiation Embrittlement of Reactor Vessel Materials," Regulatory Guide 1.99, Revision 2, May 1988.

[11] QC-2 RPV Geometry Drawing, 151827, Revision 2, by The Babcock & Wilcox Company.

[12] Raju, I.S. and Newman, J.C., "Stress Intensity Factor Influence Coefficients for Internal and External Surface Cracks in Cylindrical Vessels," PVP Volume 58, 1982.

[13] Quad Cities Thermal Cycle Diagram, GE Drawing No. 921D265.

[14] GE Document 26A5588, Power Uprate Certified Design Specification for Quad Cities 1, 2 Reactor Vessel, Sept. 2000.

[15] Reactor Cycles – BWR/6 Standard," GE Drawing No. 795E949, Revision 0, July 1981 (GE Proprietary).

Table 1 Calculated Values of Applied J-Integral for 1.15xAccumulation Pressure

Pressure (psi)=	1581
Vessel Ri (in.)=	125.7
Vessel Th (in.)=	6.13
Cooling Rate (F/Hr)=	100
a0 (in.)=	1.5325
E (ksi)=	27700
YS (ksi)=	69

AXIAL FLAW CALCULATION

a	F1	F3	Kp	Kt	ae	F1'	F3'	K,total	J,app
1.53	1.045	1.062	77.95	9.88	1.618	1.052	1.062	90.55	269.35
1.58	1.049	1.063	79.53	9.89	1.672	1.057	1.061	92.22	279.37
1.63	1.053	1.062	81.11	9.88	1.725	1.062	1.060	93.88	289.57
1.68	1.058	1.061	82.69	9.87	1.778	1.067	1.058	95.55	299.94
1.73	1.062	1.060	84.27	9.86	1.831	1.072	1.055	97.22	310.50
1.78	1.067	1.057	85.85	9.84	1.885	1.077	1.051	98.89	321.25
1.83	1.072	1.055	87.45	9.81	1.938	1.083	1.047	100.56	332.21
1.88	1.077	1.051	89.04	9.78	1.991	1.088	1.042	102.24	343.37
1.93	1.082	1.048	90.64	9.75	2.045	1.094	1.037	103.92	354.77
1.98	1.087	1.043	92.25	9.70	2.098	1.100	1.031	105.61	366.39
2.03	1.093	1.038	93.87	9.66	2.152	1.106	1.024	107.30	378.25
2.08	1.098	1.033	95.50	9.61	2.206	1.112	1.017	109.01	390.37
2.13	1.104	1.027	97.13	9.55	2.259	1.119	1.009	110.72	402.75
2.18	1.110	1.020	98.78	9.49	2.313	1.125	1.001	112.45	415.40
2.23	1.115	1.013	100.44	9.43	2.367	1.132	0.992	114.19	428.34
2.28	1.121	1.006	102.11	9.36	2.421	1.139	0.983	115.94	441.58
2.33	1.128	0.998	103.79	9.28	2.475	1.146	0.973	117.70	455.12
2.38	1.134	0.990	105.48	9.21	2.529	1.153	0.963	119.48	468.98
2.43	1.140	0.981	107.19	9.12	2.583	1.161	0.952	121.28	483.18
2.48	1.147	0.972	108.91	9.04	2.638	1.168	0.940	123.09	497.72
2.53	1.154	0.962	110.64	8.95	2.692	1.176	0.929	124.92	512.62

CIRCUMFERENTIAL FLAW CALCULATION

a	F2	F3	Kp	Kt	ae	F2'	F3'	K,total	J,app
1.53	0.965	1.062	37.66	9.88	1.558	0.966	1.062	47.92	75.44
1.58	0.968	1.063	38.40	9.89	1.608	0.970	1.062	48.67	77.83
1.63	0.972	1.062	39.14	9.88	1.659	0.973	1.062	49.41	80.22
1.68	0.975	1.061	39.88	9.87	1.710	0.977	1.060	50.15	82.61
1.73	0.978	1.060	40.61	9.86	1.761	0.980	1.058	50.87	85.02
1.78	0.982	1.057	41.34	9.84	1.812	0.984	1.056	51.59	87.43
1.83	0.985	1.055	42.07	9.81	1.862	0.988	1.053	52.30	89.85
1.88	0.989	1.051	42.79	9.78	1.913	0.991	1.049	53.00	92.28
1.93	0.993	1.048	43.52	9.75	1.964	0.995	1.045	53.70	94.72
1.98	0.996	1.043	44.24	9.70	2.015	0.999	1.040	54.39	97.17
2.03	1.000	1.038	44.96	9.66	2.066	1.003	1.035	55.07	99.63
2.08	1.004	1.033	45.69	9.61	2.117	1.007	1.029	55.75	102.10
2.13	1.008	1.027	46.41	9.55	2.167	1.011	1.022	56.42	104.58
2.18	1.012	1.020	47.13	9.49	2.218	1.014	1.015	57.09	107.08
2.23	1.016	1.013	47.85	9.43	2.269	1.019	1.008	57.76	109.59
2.28	1.020	1.006	48.57	9.36	2.320	1.023	1.000	58.42	112.11
2.33	1.024	0.998	49.30	9.28	2.371	1.027	0.992	59.07	114.65
2.38	1.028	0.990	50.02	9.21	2.422	1.031	0.983	59.73	117.20
2.43	1.032	0.981	50.74	9.12	2.472	1.035	0.973	60.38	119.77
2.48	1.036	0.972	51.47	9.04	2.523	1.039	0.964	61.03	122.36
2.53	1.040	0.962	52.20	8.95	2.574	1.044	0.954	61.67	124.96

Table 2 Calculated Values of Applied J-Integral for 1.25xAccumulation Pressure

Pressure (psi)=	1719
Vessel Ri (in.)=	125.7
Vessel Th (in.)=	6.13
Cooling Rate (F/Hr)=	100
a0 (in.)=	1.5325
E (ksi)=	27700
YS (ksi)=	69

AXIAL FLAW CALCULATION

a	F1	F3	Kp	Kt	ae	F1'	F3'	K,total	J,app
1.53	1.045	1.062	84.76	9.88	1.632	1.053	1.062	98.06	315.91
1.58	1.049	1.063	86.47	9.89	1.686	1.058	1.061	99.90	327.83
1.63	1.053	1.062	88.19	9.88	1.740	1.063	1.059	101.73	339.97
1.68	1.058	1.061	89.90	9.87	1.793	1.068	1.057	103.56	352.32
1.73	1.062	1.060	91.62	9.86	1.847	1.073	1.054	105.39	364.92
1.78	1.067	1.057	93.35	9.84	1.901	1.079	1.050	107.23	377.75
1.83	1.072	1.055	95.08	9.81	1.955	1.084	1.046	109.07	390.85
1.88	1.077	1.051	96.81	9.78	2.009	1.090	1.041	110.92	404.20
1.93	1.082	1.048	98.56	9.75	2.063	1.096	1.035	112.78	417.84
1.98	1.087	1.043	100.31	9.70	2.117	1.102	1.029	114.64	431.77
2.03	1.093	1.038	102.07	9.66	2.172	1.108	1.022	116.52	446.01
2.08	1.098	1.033	103.83	9.61	2.226	1.115	1.014	118.40	460.56
2.13	1.104	1.027	105.61	9.55	2.280	1.121	1.006	120.30	475.44
2.18	1.110	1.020	107.40	9.49	2.335	1.128	0.998	122.21	490.67
2.23	1.115	1.013	109.21	9.43	2.389	1.135	0.988	124.14	506.25
2.28	1.121	1.006	111.02	9.36	2.444	1.142	0.979	126.08	522.20
2.33	1.128	0.998	112.85	9.28	2.499	1.149	0.968	128.04	538.55
2.38	1.134	0.990	114.69	9.21	2.554	1.157	0.958	130.01	555.30
2.43	1.140	0.981	116.54	9.12	2.608	1.164	0.946	132.01	572.46
2.48	1.147	0.972	118.42	9.04	2.664	1.172	0.935	134.02	590.07
2.53	1.154	0.962	120.30	8.95	2.719	1.180	0.923	136.06	608.12

CIRCUMFERENTIAL FLAW CALCULATION

a	F2	F3	Kp	Kt	ae	F2'	F3'	K,total	J,app
1.53	0.965	1.062	40.95	9.88	1.561	0.967	1.062	51.30	86.46
1.58	0.968	1.063	41.76	9.89	1.612	0.970	1.062	52.12	89.24
1.63	0.972	1.062	42.56	9.88	1.663	0.974	1.062	52.93	92.02
1.68	0.975	1.061	43.36	9.87	1.714	0.977	1.060	53.73	94.82
1.73	0.978	1.060	44.15	9.86	1.765	0.981	1.058	54.52	97.64
1.78	0.982	1.057	44.95	9.84	1.816	0.984	1.056	55.30	100.46
1.83	0.985	1.055	45.74	9.81	1.867	0.988	1.052	56.07	103.30
1.88	0.989	1.051	46.53	9.78	1.918	0.992	1.049	56.84	106.15
1.93	0.993	1.048	47.32	9.75	1.969	0.995	1.044	57.60	109.01
1.98	0.996	1.043	48.10	9.70	2.020	0.999	1.039	58.36	111.89
2.03	1.000	1.038	48.89	9.66	2.071	1.003	1.034	59.11	114.78
2.08	1.004	1.033	49.67	9.61	2.122	1.007	1.028	59.85	117.69
2.13	1.008	1.027	50.46	9.55	2.173	1.011	1.022	60.59	120.62
2.18	1.012	1.020	51.24	9.49	2.224	1.015	1.015	61.33	123.56
2.23	1.016	1.013	52.03	9.43	2.275	1.019	1.007	62.06	126.52
2.28	1.020	1.006	52.81	9.36	2.326	1.023	0.999	62.79	129.50
2.33	1.024	0.998	53.60	9.28	2.377	1.027	0.991	63.51	132.50
2.38	1.028	0.990	54.39	9.21	2.428	1.031	0.982	64.23	135.53
2.43	1.032	0.981	55.17	9.12	2.479	1.036	0.972	64.95	138.57
2.48	1.036	0.972	55.96	9.04	2.530	1.040	0.962	65.66	141.64
2.53	1.040	0.962	56.75	8.95	2.581	1.044	0.952	66.37	144.73

Table 3 Calculated Values of Applied J-Integral for Level C Transient

Emergency Condition: transient event 24

		Kt Coefficients		Clad Stress	
Pressure (psi)=	1050				
Vessel Ri (in.)=	125.7				
Vessel Th (in.)=	6.13	a=	8.831288		
Clad thickness (in.)=	0.19	b=	74.92595	S (ksi)=	6
a0 (in.)=	0.803	c=	-107.681		
E (ksi)=	27700	d=	63.6289		
YS (ksi)=	69	e=	-14.3416		

AXIAL FLAW CALCULATION

a	F1	Kt	Kp	Kclad	ae	F1'	K't	K'p	K'clad	Ktotal	Japp
0.80	0.999	26.55	35.84	1.99	0.849	1.001	26.31	36.93	1.93	65.17	139.52
0.85	1.001	26.29	37.02	1.92	0.900	1.004	26.02	38.12	1.86	66.00	143.10
0.90	1.004	26.00	38.18	1.86	0.952	1.006	25.69	39.29	1.81	66.78	146.53
0.95	1.006	25.68	39.32	1.81	1.003	1.009	25.34	40.44	1.76	67.54	149.84
1.00	1.009	25.34	40.44	1.75	1.054	1.012	24.98	41.57	1.71	68.26	153.07
1.05	1.012	24.99	41.55	1.71	1.105	1.015	24.61	42.69	1.66	68.96	156.25
1.10	1.015	24.63	42.65	1.67	1.156	1.018	24.23	43.80	1.62	69.65	159.37
1.15	1.018	24.25	43.73	1.63	1.207	1.021	23.84	44.89	1.59	70.32	162.45
1.20	1.021	23.87	44.81	1.59	1.258	1.024	23.43	45.99	1.55	70.97	165.47
1.25	1.024	23.47	45.88	1.55	1.309	1.028	23.01	47.07	1.52	71.60	168.40
1.30	1.027	23.06	46.94	1.52	1.360	1.032	22.56	48.15	1.49	72.19	171.20
1.35	1.031	22.62	48.00	1.49	1.411	1.035	22.07	49.22	1.46	72.74	173.84
1.40	1.035	22.15	49.05	1.46	1.462	1.039	21.53	50.29	1.43	73.25	176.25
1.45	1.039	21.63	50.10	1.44	1.513	1.043	20.92	51.35	1.40	73.68	178.36
1.50	1.042	21.04	51.15	1.41	1.563	1.047	20.24	52.42	1.38	74.04	180.08
1.55	1.047	20.39	52.20	1.38	1.614	1.052	19.46	53.48	1.36	74.29	181.32
1.60	1.051	19.64	53.25	1.36	1.664	1.056	18.55	54.54	1.33	74.43	181.97
1.65	1.055	18.77	54.30	1.34	1.715	1.061	17.51	55.59	1.31	74.42	181.94
1.70	1.060	17.77	55.35	1.32	1.765	1.065	16.31	56.64	1.29	74.25	181.10
1.75	1.064	16.61	56.40	1.30	1.815	1.070	14.92	57.70	1.28	73.89	179.34
1.80	1.069	15.26	57.45	1.28	1.864	1.075	13.31	58.74	1.26	73.31	176.57

CIRCUMFERENTIAL FLAW CALCULATION

a	F1	Kt	Kp	Kclad	ae	F1'	K't	K'p	K'clad	Ktotal	Japp
0.80	0.921	26.55	17.29	1.99	0.826	0.923	26.43	17.57	1.96	45.95	69.38
0.85	0.924	26.29	17.87	1.92	0.877	0.925	26.16	18.15	1.89	46.19	70.11
0.90	0.927	26.00	18.44	1.86	0.927	0.928	25.85	18.71	1.83	46.40	70.72
0.95	0.930	25.68	19.00	1.81	0.977	0.931	25.52	19.27	1.78	46.57	71.25
1.00	0.932	25.34	19.56	1.75	1.027	0.934	25.17	19.82	1.73	46.72	71.72
1.05	0.935	24.99	20.10	1.71	1.077	0.937	24.81	20.36	1.69	46.86	72.14
1.10	0.938	24.63	20.63	1.67	1.128	0.940	24.44	20.89	1.65	46.98	72.52
1.15	0.941	24.25	21.16	1.63	1.178	0.942	24.07	21.42	1.61	47.09	72.86
1.20	0.944	23.87	21.68	1.59	1.228	0.946	23.68	21.94	1.57	47.19	73.15
1.25	0.947	23.47	22.20	1.55	1.278	0.949	23.27	22.46	1.54	47.26	73.39
1.30	0.950	23.06	22.71	1.52	1.328	0.952	22.84	22.97	1.51	47.32	73.55
1.35	0.953	22.62	23.22	1.49	1.378	0.955	22.39	23.47	1.48	47.34	73.62
1.40	0.956	22.15	23.72	1.46	1.428	0.958	21.89	23.97	1.45	47.32	73.55
1.45	0.960	21.63	24.22	1.44	1.478	0.961	21.34	24.47	1.42	47.24	73.31
1.50	0.963	21.04	24.72	1.41	1.528	0.965	20.73	24.97	1.40	47.09	72.86
1.55	0.966	20.39	25.22	1.38	1.578	0.968	20.03	25.46	1.37	46.86	72.14
1.60	0.970	19.64	25.71	1.36	1.627	0.971	19.23	25.95	1.35	46.53	71.12
1.65	0.973	18.77	26.20	1.34	1.677	0.975	18.31	26.43	1.33	46.07	69.73
1.70	0.976	17.77	26.68	1.32	1.726	0.978	17.25	26.91	1.31	45.47	67.92
1.75	0.980	16.61	27.17	1.30	1.776	0.981	16.02	27.39	1.29	44.70	65.64
1.80	0.983	15.26	27.65	1.28	1.825	0.985	14.60	27.86	1.27	43.74	62.85

Table 4 Calculated Values of Applied J-Integral for Level D Transient

Faulted Condition: transient event 27

Pressure (psi)=	20				
Vessel Ri (in.)=	125.7	Kt Coefficients		Clad Stress	
Vessel Th (in.)=	6.13	a=	14.01		
Clad thickness (in.)=	0.19	b=	130.91	S (ksi)=	16.5
a0 (in.)=	0.803	c=	-155.73		
E (ksi)=	27700	d=	89.845		
YS (ksi)=	69	e=	-20.64		

AXIAL FLAW CALCULATION

a	F1	Kt	Kp	Kclad	ae	F1'	K't	K'p	K'clad	Ktotal	Japp
0.80	0.999	56.65	0.68	5.47	0.847	1.001	57.14	0.70	5.30	63.15	131.00
0.85	1.001	57.20	0.71	5.28	0.897	1.004	57.62	0.72	5.13	63.48	132.39
0.90	1.004	57.67	0.73	5.12	0.948	1.006	58.03	0.75	4.98	63.76	133.56
0.95	1.006	58.07	0.75	4.96	0.998	1.009	58.39	0.77	4.84	63.99	134.53
1.00	1.009	58.42	0.77	4.83	1.049	1.011	58.69	0.79	4.71	64.19	135.35
1.05	1.012	58.71	0.79	4.70	1.099	1.014	58.94	0.81	4.59	64.34	136.00
1.10	1.015	58.96	0.81	4.58	1.149	1.017	59.15	0.83	4.48	64.46	136.49
1.15	1.018	59.16	0.83	4.47	1.199	1.021	59.31	0.85	4.38	64.53	136.82
1.20	1.021	59.32	0.85	4.37	1.249	1.024	59.41	0.87	4.28	64.56	136.94
1.25	1.024	59.42	0.87	4.27	1.299	1.027	59.45	0.89	4.19	64.54	136.83
1.30	1.027	59.45	0.89	4.18	1.349	1.031	59.42	0.91	4.11	64.44	136.43
1.35	1.031	59.42	0.91	4.10	1.399	1.034	59.31	0.93	4.03	64.27	135.68
1.40	1.035	59.29	0.93	4.02	1.449	1.038	59.08	0.95	3.95	63.99	134.51
1.45	1.039	59.06	0.95	3.95	1.499	1.042	58.74	0.97	3.88	63.59	132.85
1.50	1.042	58.70	0.97	3.88	1.548	1.046	58.25	0.99	3.82	63.06	130.62
1.55	1.047	58.19	0.99	3.81	1.597	1.050	57.59	1.01	3.75	62.35	127.72
1.60	1.051	57.50	1.01	3.74	1.646	1.055	56.73	1.03	3.69	61.46	124.08
1.65	1.055	56.60	1.03	3.68	1.695	1.059	55.66	1.05	3.64	60.34	119.62
1.70	1.060	55.45	1.05	3.63	1.743	1.063	54.33	1.07	3.58	58.98	114.28
1.75	1.064	54.03	1.07	3.57	1.791	1.068	52.72	1.09	3.53	57.34	108.02

CIRCUMFERENTIAL FLAW CALCULATION

a	F1	Kt	Kp	Kclad	ae	F1'	K't	K'p	K'clad	Ktotal	Japp
0.80	0.921	56.65	0.33	5.47	0.846	0.924	57.14	0.34	5.30	62.78	129.48
0.85	0.924	57.20	0.34	5.28	0.897	0.926	57.62	0.35	5.14	63.10	130.82
0.90	0.927	57.67	0.35	5.12	0.947	0.929	58.03	0.36	4.98	63.37	131.93
0.95	0.930	58.07	0.36	4.96	0.998	0.932	58.38	0.37	4.84	63.59	132.86
1.00	0.932	58.42	0.37	4.83	1.048	0.935	58.68	0.38	4.71	63.78	133.62
1.05	0.935	58.71	0.38	4.70	1.098	0.938	58.94	0.39	4.59	63.92	134.23
1.10	0.938	58.96	0.39	4.58	1.149	0.941	59.15	0.40	4.48	64.03	134.68
1.15	0.941	59.16	0.40	4.47	1.199	0.944	59.30	0.41	4.38	64.09	134.96
1.20	0.944	59.32	0.41	4.37	1.249	0.947	59.41	0.42	4.28	64.11	135.04
1.25	0.947	59.42	0.42	4.27	1.299	0.950	59.45	0.43	4.19	64.08	134.88
1.30	0.950	59.45	0.43	4.18	1.349	0.953	59.42	0.44	4.11	63.97	134.45
1.35	0.953	59.42	0.44	4.10	1.399	0.956	59.31	0.45	4.03	63.79	133.67
1.40	0.956	59.29	0.45	4.02	1.448	0.959	59.09	0.46	3.95	63.50	132.47
1.45	0.960	59.06	0.46	3.95	1.498	0.963	58.74	0.47	3.88	63.10	130.79
1.50	0.963	58.70	0.47	3.88	1.547	0.966	58.26	0.48	3.82	62.55	128.54
1.55	0.966	58.19	0.48	3.81	1.596	0.969	57.60	0.49	3.75	61.84	125.63
1.60	0.970	57.50	0.49	3.74	1.645	0.972	56.75	0.50	3.69	60.94	121.99
1.65	0.973	56.60	0.50	3.68	1.694	0.976	55.67	0.51	3.64	59.82	117.55
1.70	0.976	55.45	0.51	3.63	1.743	0.979	54.35	0.52	3.58	58.45	112.23
1.75	0.980	54.03	0.52	3.57	1.791	0.983	52.75	0.52	3.53	56.80	106.01

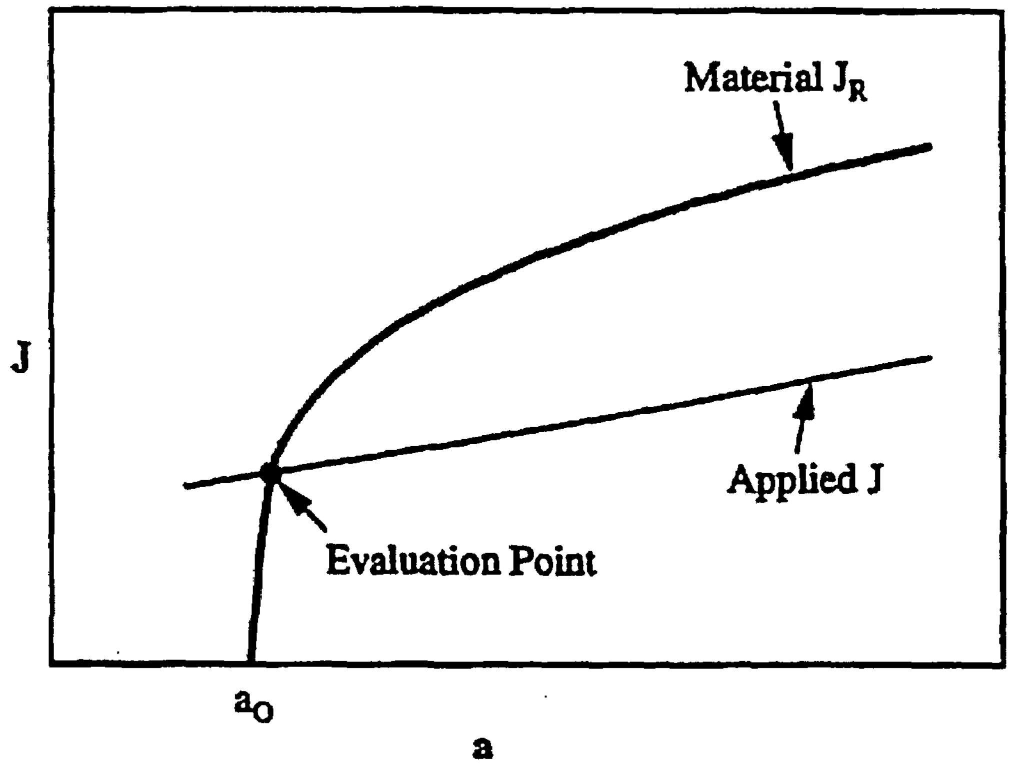

Figure 1 Illustration of Ductile Crack Growth Stability Evaluation

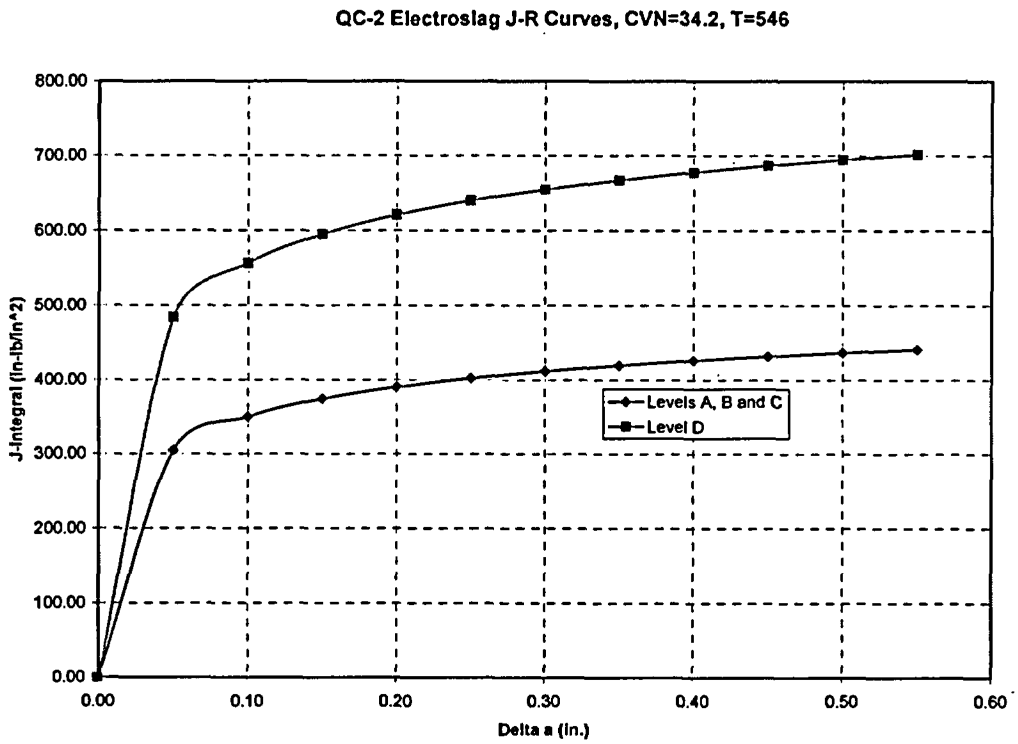

Figure 2 Quad Cities Electroslag Weld J-Integral Resistance Curves

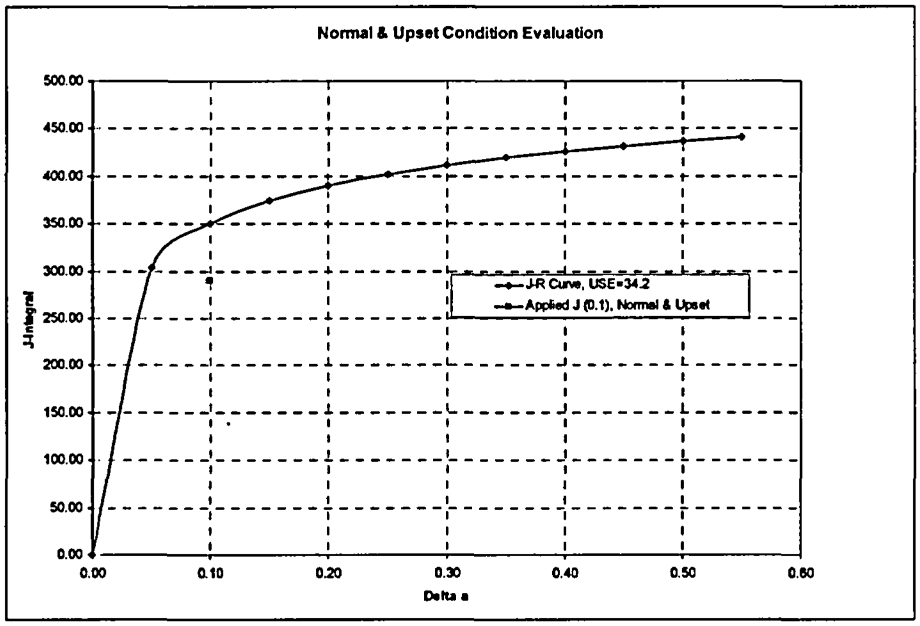

Figure 3 $J_{0.1}$ Criterion Evaluation for Axial Flaw with Electroslag J-R Curve

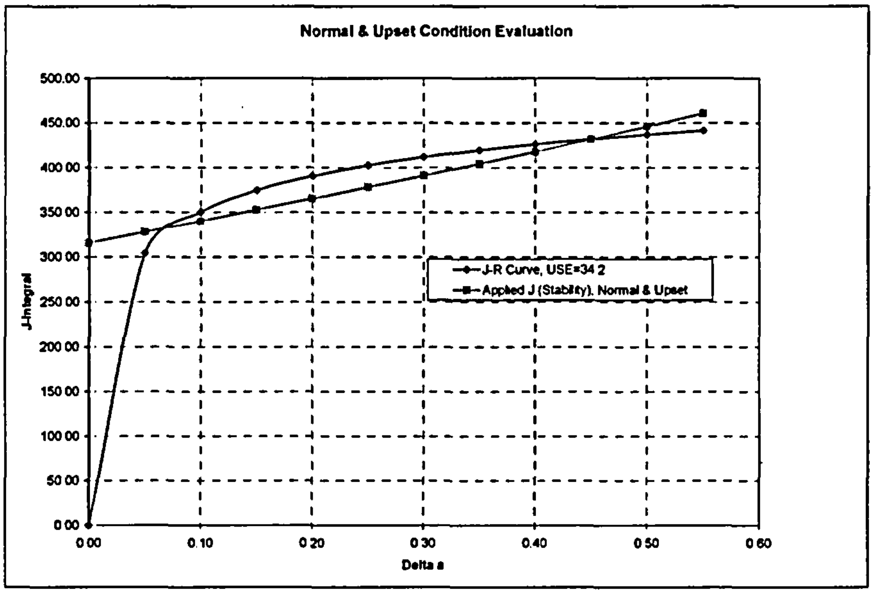

Figure 4 Flaw Stability Criterion Evaluation for Axial Flaw with Electroslag J-R Curve

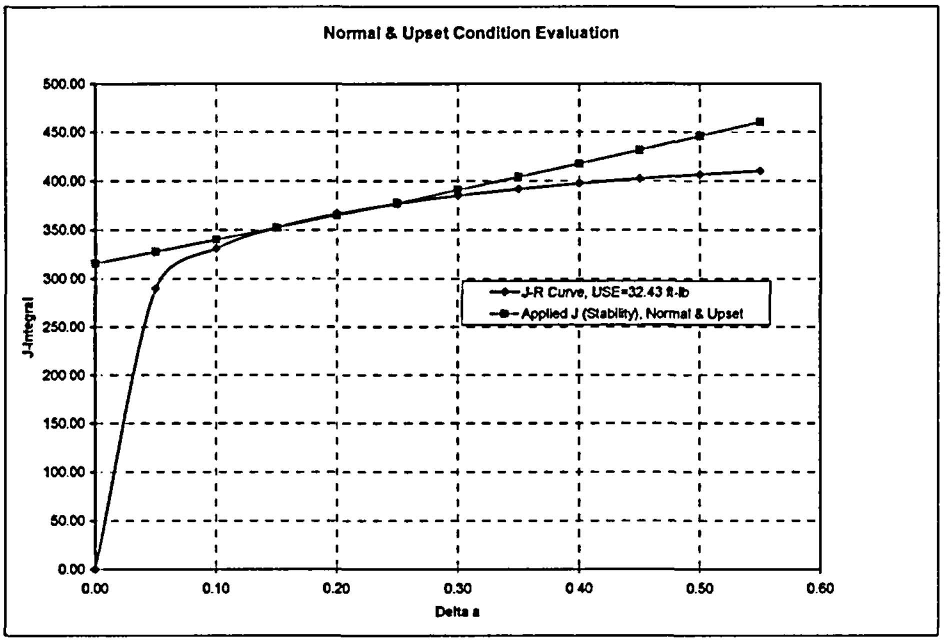

Figure 5 Required Minimum Electroslag USE to Meet Stability Criterion

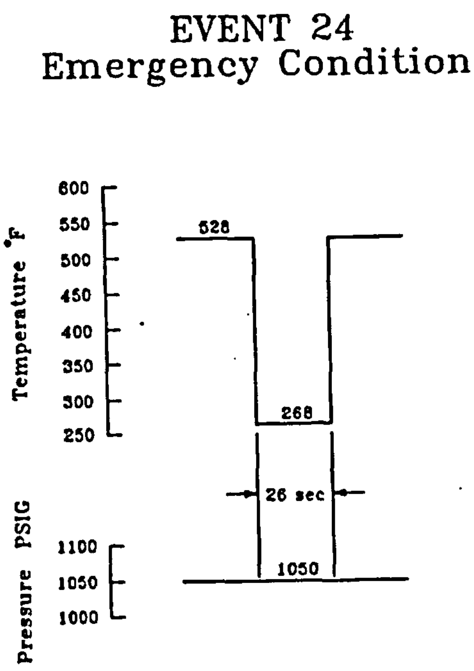

Figure 6 Pressure & Temperature Conditions During Improper Start of Cold Recirculation Loop Transient (Event 24)

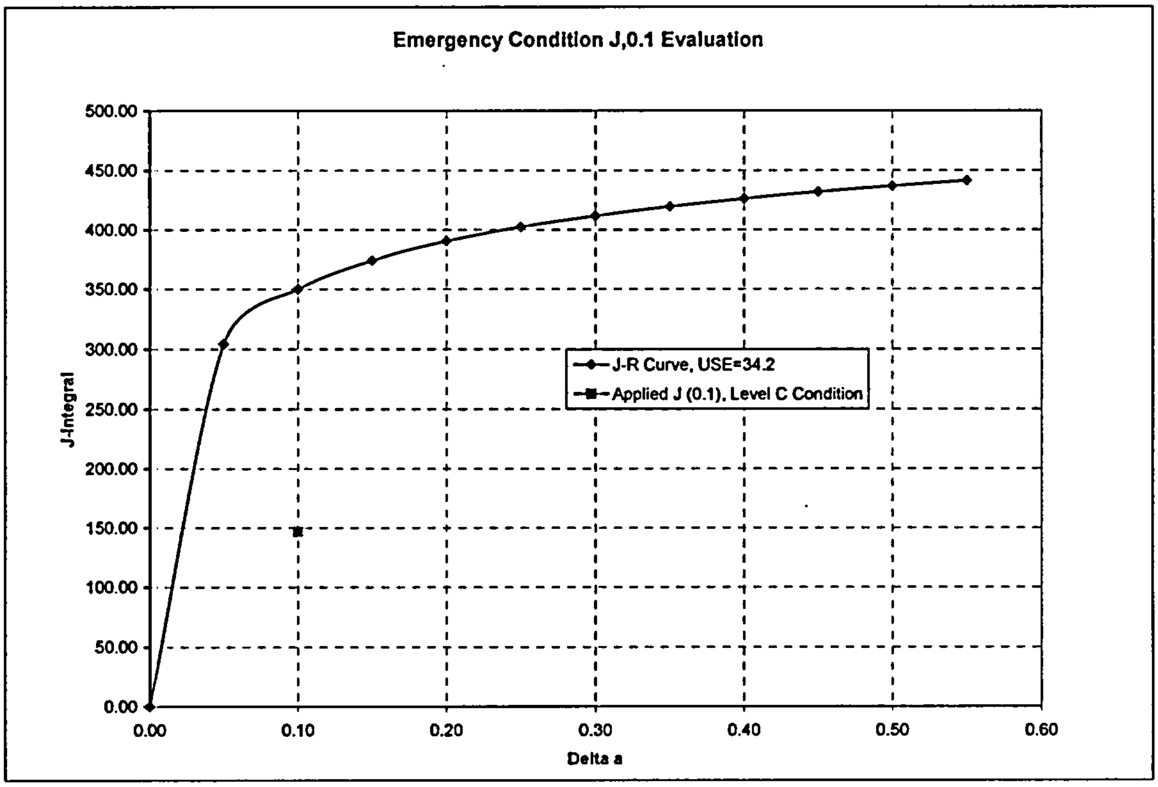

Figure 7 $J_{0.1}$ Evaluation for Level C Condition

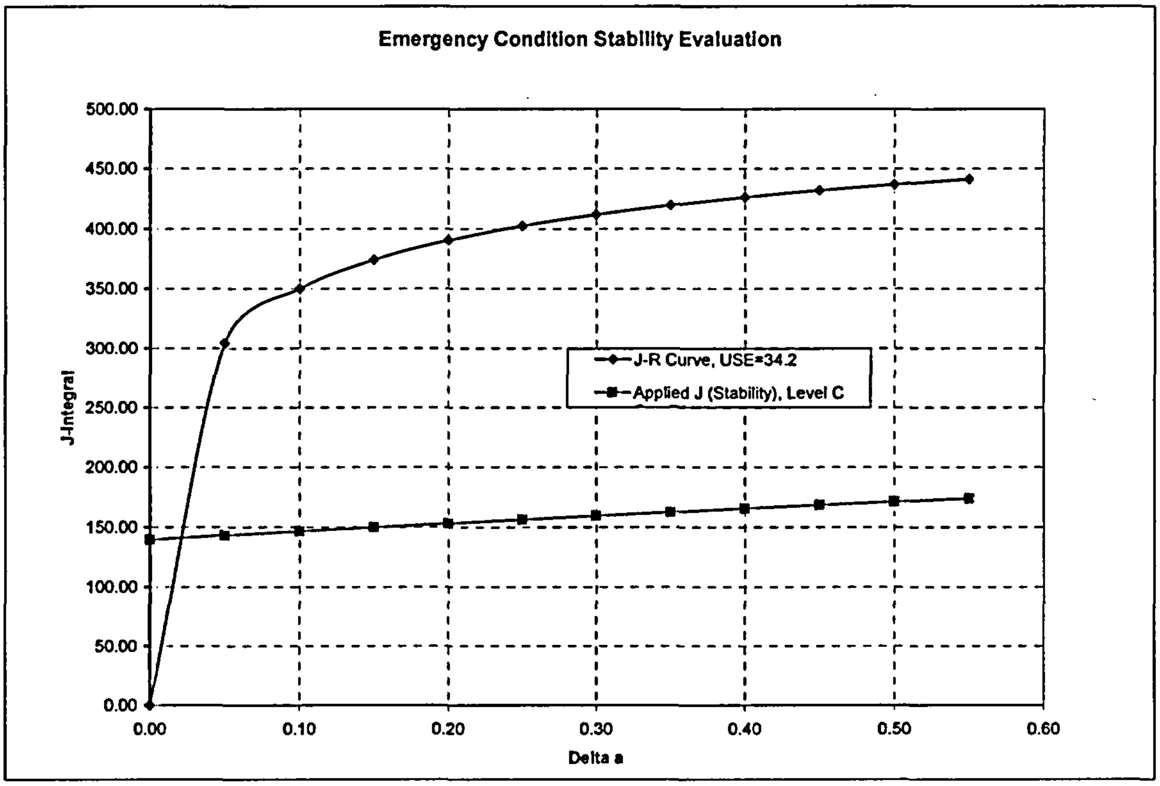

Figure 8 Crack Growth Stability Criterion Evaluation for Level C Condition

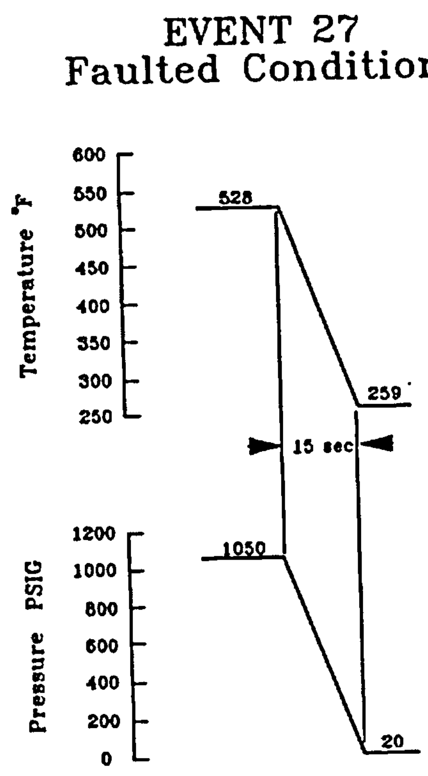

Figure 9 Limiting level D Transient (Event 27)

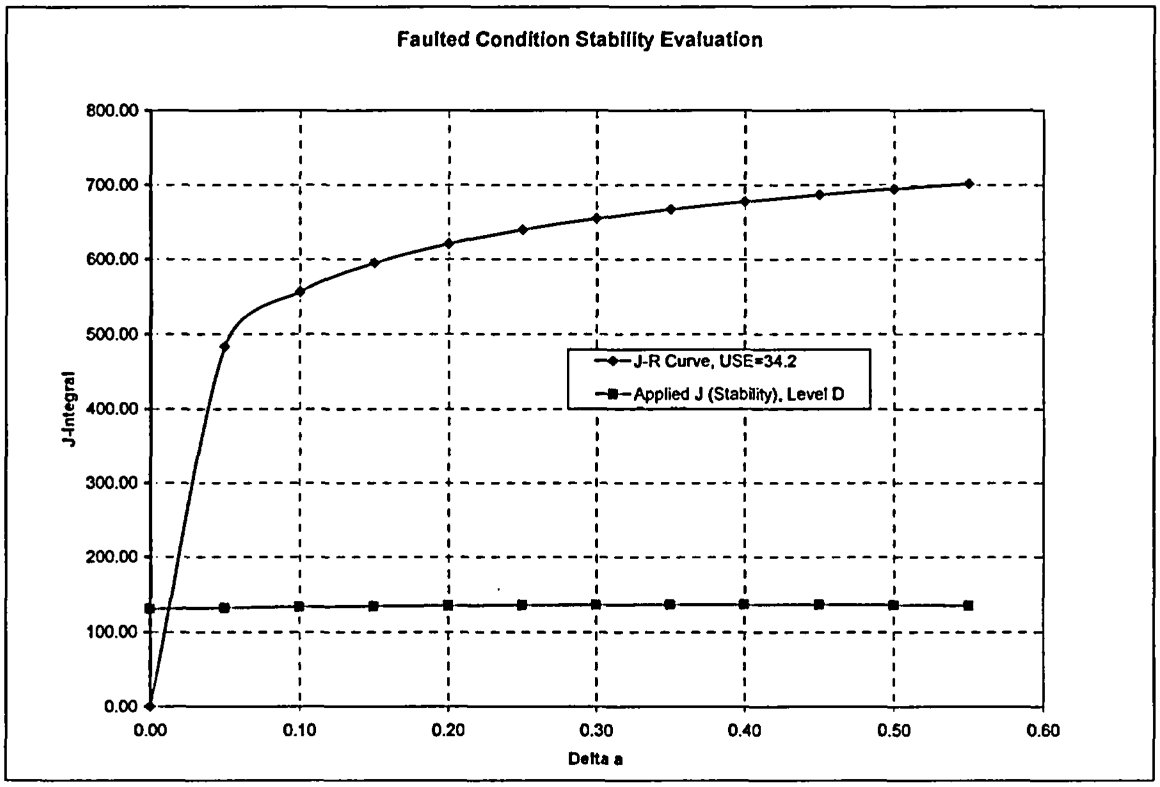

Figure 10 Crack Growth Stability Criterion Evaluation for Level D Condition