NUREG/CR-6023
ORNL/TM-12340

Generic Analyses for Evaluation of Low Charpy Upper-Shelf Energy Effects on Safety Margins Against Fracture of Reactor Pressure Vessel Materials

prepared by
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Manuscript Completed: April 1993
Date Published: July 1993

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Prepared for
Division of Engineering
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
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Abstract

Appendix G to 10 CFR Part 50 requires that reactor pressure vessel beltline materials maintain Charpy upper-shelf energies of no less than 50 ft-lb during the plant operating life, unless it is demonstrated in a manner approved by the Nuclear Regulatory Commission (NRC), that lower values of Charpy upper-shelf energy provide margins of safety against fracture equivalent to those in Appendix G to Section III of the ASME Code.

Analyses based on acceptance criteria and analysis methods adopted in the ASME Code Case N-512 are described herein. Additional information on material properties was provided by the NRC, Office of Nuclear Regulatory Research, Materials Engineering Branch. These cases, specified by the NRC, represent generic applications to boiling water reactor and pressurized water reactor vessels. This report is designated as HSST Report No. 140.

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1 Introduction

Appendix G to 10 CFR Part 50 [1] requires that reactor pressure vessel (RPV) beltline materials maintain Charpy upper-shelf energies (CVN) of no less than 50 ft-lb (68 J) during the plant operating life, unless it is demonstrated in a manner approved by the Director, Office of Nuclear Reactor Regulation, that lower values of Charpy upper-shelf energy provide margins of safety against fracture equivalent to those in Appendix G to Section III of the ASME Code [2].

ASME Code Case N-512 [3] describes acceptance criteria and analytical methodologies for the assessment of the integrity of reactor vessels with low CVN. Generic analyses that utilize the procedures and acceptance criteria that are

consistent with the approach described in Code Case N-512 are described herein. These analyses, specified by the NRC, represent applications to both boiling water reactor (BWR) and pressurized water reactor (PWR) vessels. The specific analyses, described in Tables 1 and 2, consist of various combinations of flaw orientations, vessel geometries, material properties, and transient conditions. One objective of the analyses was to determine the limiting values of CVN and, where applicable, neutron fluence that satisfy the acceptance criteria provided in the Code Case N-512. Another objective was to provide several representative applications of the analytical methodologies.

Table 1. Combinations of vessel geometries and J_R models for which analyses were performed for levels A and B and level C

Material (J _R model)				
PWR vessel geometry	Linde 80 weld (Charpy)	Linde 80 weld (copper-fluence)	Low-toughness plate (A-302B)	Generic weld
PWR 1	X	X		
PWR 2	X	X		
PWR 3	X	X		
PWR 4			X	
BWR vessel geometry				
BWR 1	X		X	X
BWR 2	X		X	X

Table 2. Combinations of vessel geometries and J_R models for which analyses were performed for ATWS transients

Material (J _R model)			
PWR vessel geometry	Linde 80 weld (Charpy)	Linde 80 weld (copper-fluence)	Low-toughness plate (A-302B)
PWR 1	X	X	
PWR 4	X	X	X
PWR 5	X	X	

2 Acceptance Criteria for Low Upper-Shelf Energy Fracture Analysis

The acceptance criteria provided in Code Case N-512 are based on the extent and stability of stable crack growth of a postulated semielliptical flaw on the inner surface of the reactor pressure vessel (RPV) wall, when subjected to various thermal and pressure operating conditions.

2.1 Level A and B Conditions

For a semielliptical inside surface flaw with a crack depth to wall thickness ratio (a/t) of 0.25 and with an aspect ratio of 6-to-1 (surface length to flaw depth):

1. The crack driving force (J_{applied}) must be shown to be less than the material toughness as given by Eq. (1) [3],

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

where J_{applied} is the J-integral value calculated for the postulated flaw under pressure and thermal loading, where the assumed pressure is 1.15 times the maximum accumulation pressure (as defined in the plant-specific Over Pressure Protection Report), with thermal loading using the plant specific heatup and cooldown conditions. The parameter $J_{0.1}$ is the J-integral characteristic of the material's resistance to ductile tearing (J_{material}), as denoted by a J_R curve test, at a crack extension of 0.10 in.

2. The flaw must be stable under ductile crack growth as given by Eq. (2) [3]:

$$\frac{\partial J_{\text{applied}}}{\partial a} < \frac{\partial J_{\text{material}}}{\partial a} \quad (2)$$

(with pressure held constant)

at $J_{\text{applied}} = J_{\text{material}}$,

where J_{applied} is calculated for the postulated flaw under combined pressure and thermal loading for level A and B conditions where the assumed pressure is 1.25 times the maximum accumulation pressure.

The material J_R curve should represent a conservative estimate of the data for the vessel material under evaluation, i.e., estimated from the mean -2 standard deviations [3].

2.2 Level C Condition

The acceptance criteria for level C condition are similar to those for levels A and B, with the exceptions of crack size and the safety factor applied to the pressure loading. Flaw sizes up to $(0.1 t_b + t_c)$ which are less than or equal to 1 in. are to be considered, and a safety factor of 1.0 is used for pressure loading. Here t_b is the vessel's base metal thickness (in.) and t_c is the clad thickness (in.).

For simplification, analyses were performed only for the normalized crack depth (a/t) of 0.10.

3 Geometries, Material Properties, and Loading Conditions

The thermoelastic material properties and vessel dimensions used in these analyses are specified in Tables 3 and 4, respectively.

3.1 Level A and B Conditions

3.1.1 PWRs

Thermal transient:

100°F/h constant cooldown rate imposed on the inner surface of the vessel wall.

The initial coolant and vessel temperatures were assumed to be 550°F.

Pressure = constant = safety factor (SF) × accumulation pressure.

The maximum accumulation pressure (P_a) is assumed to be 10% above the design pressure of 2.5 ksi:

for acceptance criterion 1: $SF = 1.15$; therefore $P_a = (1.15)(2.5)(1.1) = 3.163$ ksi
for acceptance criterion 2: $SF = 1.25$; therefore $P_a = (1.25)(2.5)(1.1) = 3.438$ ksi.

3.1.2 BWRs

Thermal transient:

100°F/h constant cooldown rate imposed on the inner surface of the vessel wall.

The initial coolant and vessel temperatures were assumed to be 550°F.

Pressure = constant = $SF \times$ accumulation pressure.

The maximum accumulation pressure is assumed to be 10% above the design pressure of 1.25 ksi:

for acceptance criterion 1: $SF = 1.15$; therefore $P_a = (1.15)(1.25)(1.1) = 1.581$ ksi
for acceptance criterion 2: $SF = 1.25$; therefore $P_a = (1.25)(1.25)(1.1) = 1.719$ ksi.

3.2 Level C Condition

3.2.1 PWRs

PWRs — Rancho Seco thermal transient and a constant pressure of 2.15 ksi (Fig. 1).

3.2.2 BWRs

BWRs — Two pressure and thermal transients as shown in Figs. 2 and 3.

Table 3. Cladding and base thermoelastic properties

BASE METAL:	
Thermal conductivity	= 24.0 BTU/hr-ft-°F
Specific heat	= 0.12 BTU/lb-°F
Density	= 489 lb/ft ³
Modulus of elasticity	= 28000 ksi
Coefficient of linear thermal expansion	= 0.00000785/°F
Poisson's ratio	= 0.3
CLADDING:	
Thermal conductivity	= 10.0 BTU/hr-ft-°F
Specific heat	= 0.12 BTU/lb-°F
Density	= 489 lb/ft ³
Modulus of elasticity	= 27000 ksi
Coefficient of linear thermal expansion	= 0.0000091/°F
Poisson's ratio	= 0.3
Convective heat transfer coefficient	= 1000 BTU/hr-ft ² -°F

Table 4. Vessel geometries

PWR geometries				
Vessel	t_b	t_c	R_i	$R_i/(t_b + t_c)$
PWR 1	8.44	0.156	86.50	10.06
PWR 2	10.63	0.156	86.50	8.02
PWR 3	9.00	0.156	77.75	8.49
PWR 4	8.625	0.156	86.00	9.79
PWR 5	8.438	0.156	85.50	9.95
BWR geometries				
Vessel	t_b	t_c	R_i	$R_i/(t_c + t_b)$
BWR 1	5.284	0.156	106.5	19.58
BWR 2	7.125	0.156	109.0	14.97
where: t_b = thickness of vessel base metal (in.) t_c = thickness of clad (in.) R_i = vessel inner radius (in.)

Figure 1. Rancho Seco PTS transient

Figure 2. BWR: level C transient 1

Figure 3. BWR: level C transient 2

4 JR Models

A material property required to perform these analyses is the J_R curve. J_R curves are a function of the material, irradiation condition, chemistry, and material temperature. Testing programs have been conducted using materials that are expected to represent the range of actual materials used in fabricating RPVs in the United States. Statistical analyses of these generic data have been performed and the resulting correlations reported in Ref. [4].

The CVN data used to establish the the J_R correlations for the Linde 80 weld (Charpy model) and generic weld may correspond to more than one orientation (not specified). For the purpose of this study, it was assumed that the data correspond to the longitudinal orientation, and that the CVN for the transverse circumferential orientation is 65% of that for the longitudinal orientation [5].

The range of CVN data used to establish the J_R correlations for the Linde 80 weld (Charpy model) and generic weld was 33–232 ft-lb [4]. Therefore, the minimum values of CVN for which these correlations are assumed to be valid (used without extrapolation) are 33 ft-lb for axial flaws and 22 ft-lb for circumferential flaws.

The range of fluence data used to establish the J_R correlations for the Linde 80 weld (copper-fluence model) was $0\text{--}36.3 \times 10^{18}$ n/cm²* [4]. The maximum value of neutron fluence for which this correlation is assumed to be valid is 3.6×10^{19} n/cm² and is applicable to both axially and circumferentially oriented flaws.

The CVN data used to establish the J_R correlation for the low-toughness plate model was obtained for the weak orientation.[†] This orientation corresponds to a circumferentially oriented flaw. This correlation was also applied to longitudinal flaws propagating radially without any correction factor. This approach tends to be conservative. The minimum value of CVN for which this correlation is assumed to be valid is 25 ft-lb and is applicable to both axially and circumferentially oriented flaws.

4.1 Linde 80 Weld (Charpy Model)

In the Linde 80 weld (Charpy model), J_R is a function of CVN and time-dependent temperature $[T(\tau)]$ given by Eq. (3) [4],

$$J_R(\tau) = (SF)\{C1 (\Delta a)^{C2} \exp[C3 (\Delta a)^{C4}]\}, \quad (3)$$

*In this report, all neutron fluences are for $(E > 1 \text{ MeV})$.

[†]Communication from S. N. M. Malik, NRC, Office of Nuclear Regulatory Research, Materials Engineering Branch.

where

$$\begin{aligned} SF &= 0.648 \\ C1 &= \exp[-3.67 + 1.45 \ln(\text{CVN}) - 0.00308 T(\tau)] \\ C2 &= 0.077 + 0.116 \ln C1 \\ C3 &= -0.0812 - 0.0092 \ln C1 \\ C4 &= -0.5 \end{aligned}$$

with units expressed as follows:

$$\begin{aligned} \Delta a &= \text{in.} \\ \text{CVN} &= \text{ft-lb} \\ T(\tau) &= \text{degrees F} \\ J_R(\tau) &= \text{in.-lb/in.}^2. \end{aligned}$$

It should be noted that specimen thickness is also a parameter (not shown above) in these correlations [4]. For simplicity, the specimen thickness was taken as 1 in. In this case the terms containing specimen thickness vanish.

$T(\tau)$ is the temperature–time history at the crack tip. The FAVOR computer program [6] was used to generate the temperature–time history of the location in the vessel wall corresponding to the crack tip. Here, SF is a correction factor for the effect of data scatter that shifts the J_R curve from a mean curve to an approximate lower-bound curve (mean –2 standard deviations) [4].

The minimum values of CVN for which this correlation is assumed to be valid are 33 and 22 ft-lb for axially and circumferentially oriented flaws, respectively.

4.2 Linde 80 Weld (Copper-Fluence Model)

In the Linde 80 weld (copper-fluence model), J_R is a function of neutron fluence, copper concentration, and time-dependent temperature $[T(\tau)]$ given by Eq. (3) with parameters [4] defined by

$$\begin{aligned} SF &= 0.645 \\ C1 &= \exp[2.43 - 0.638 \text{ Cu} (\text{fluence})^{0.543} - 0.00252 T(\tau)] \\ C2 &= 0.077 + 0.116 \ln C1 \\ C3 &= -0.0812 - 0.0092 \ln C1 \\ C4 &= -0.5. \end{aligned}$$

Here, Cu is the copper concentration expressed in weight percent and fluence is the neutron fluence (normalized by 10^{18} n/cm²) at the crack tip. Temperature is expressed in degrees F. Units for J_R and Δa are the same as those expressed in Sect. 4.1.

The maximum value of neutron fluence for which the J_R correlation is assumed to be valid is 3.6×10^{19} n/cm² [4]; this value is applicable to both axially and circumferentially

oriented flaws. All neutron fluences in this report are values at the crack tip.

4.3 Generic Weld Model

In the generic weld model, J_R is a function of CVN and time-dependent temperature [T(τ)] as given by Eq. (3) with parameters [4] defined by

$$\begin{aligned} SF &= 0.629 \\ C1 &= \exp[-4.12 + 1.49 \ln(\text{CVN}) - 0.00249 T(\tau)] \\ C2 &= 0.077 + 0.116 \ln C1 \\ C3 &= -0.0812 - 0.0092 \ln C1 \\ C4 &= -0.5. \end{aligned}$$

The units are identical to those specified in Sect. 4.1.

The minimum values of CVN for which this correlation is assumed to be valid are 33 and 22 ft-lb for axially and circumferentially oriented flaws, respectively.

4.4 Low-Toughness Plate Model

In the low-toughness plate model, J_R is a function of CVN and time-dependent temperature [T(τ)] as given by Eq. (4),*

$$J_R(\tau) = (SF) \{C1 (\Delta a)^{C2} [f(\text{CVN})] [f(T)]\}, \quad (4)$$

where

$$\begin{aligned} C1 &= 946.82 \\ C2 &= 0.1334 \\ SF &= 1.0 \\ f(\text{CVN}) &= [11.75 * \text{CVN} + 108] / 695.5 \\ f(T) &= [1 - 0.4182(T(\tau) - 180)/420] \text{ with } 180^\circ\text{F} \leq T(\tau) \leq 600^\circ\text{F}. \end{aligned}$$

The units are identical to those specified in Sect. 4.1.

The f(CVN) is used to correct the J-R curve for upper-shelf energy levels. The f(T) is used to correct the J-R curve for temperature [4]. The coefficients C₁ and C₂ are based on a 6-in.-thick ASTM 6T-CT specimen tested in the weak (T-L) orientation which is applicable to RPV circumferential flaws.

The minimum value of CVN for which this correlation is assumed to be valid is 25 ft-lb; this value is applicable to both axially and circumferentially oriented flaws.

*Communication from S. N. M. Malik, NRC, Office of Nuclear Regulatory Research, Materials Engineering Branch.

5 Analysis Methodologies

The analyses required to determine the limiting values (minimum CVN or maximum neutron fluence) that satisfy the acceptance criteria consist of the following steps.

5.1 Satisfying Acceptance Criterion 1

To satisfy acceptance criterion 1, the material fracture resistance (J_R) must be greater than J_{applied} for a crack of specified initial depth (a_0), extended by 0.10 in. (Δa), for all transient times. The objective is to find the minimum value of CVN (or maximum value of neutron fluence), that produces a J_R time-history curve for a specified $\Delta a = 0.10$ in. that is greater than the J_{applied} time-history curve for all transient times.

5.1.1 Generation of J_{applied} -Time History

The calculation of the J_{applied} time history consists of two major steps: Step I is to calculate the effective flaw depth (a_e) that includes a plastic zone correction for the flaw depth ($a = a_0 + \Delta a$); and Step II is to calculate the J_{applied} for small-scale yielding based on this effective flaw depth.

The flow chart logic for this methodology is illustrated in Fig. 4 and is explained below.

Step I:

The stress intensity factor due to internal pressure is calculated for axially oriented flaws according to Eq. (5) [3],

$$K_{Ip} = (SF) P_a \{ 1 + (R_i/t) (\pi a)^{0.5} F_1 \}, \quad (5)$$

where $F_1 = 0.982 + 1.006 (a/t)^2$, and for circumferentially oriented flaws according to Eq. (6),

$$K_{Ip} = (SF) P_a \{ 1 + (R_i/2t) (\pi a)^{0.5} F_2 \}, \quad (6)$$

where $F_2 = 0.885 + 0.233 (a/t) + 0.345 (a/t)^2$. Equations (5) and (6) include the effect of pressure acting on the crack face.

In this study, detailed analyses were performed to determine the time-dependent thermally induced stress intensity factor. The FAVOR [6] and VISA-II [7] computer codes were used to generate the stress intensity factor associated with the radial thermal gradient (K_{It}) for discrete axially oriented crack depths at selected transient times. For each selected

transient time, a least squares 4th order polynomial was fitted through the discrete K_{It} results as a function of crack depth to wall thickness (a/t) ratio. Thus, K_{It} can then be predicted for any crack depth.

Stress intensity factors were calculated using superposition techniques and stress intensity factor influence coefficients. Influence coefficients were not available to calculate thermally induced stress intensity factors for a semielliptical (with a length equal to six times the depth) circumferentially oriented flaw. Therefore, K_{It} calculated for axially oriented flaws was also applied to circumferentially oriented flaws, under the assumption that such an approximation is conservative. This assumption is based on the observation that stress intensity factors for infinite length axial flaws are equal to or greater than those for continuous circumferential flaws of the same depth.

The stress intensity factor influence coefficients used in these analyses for both PWR and BWR are for vessels with an internal radius-to-wall thickness ratio of 10, whereas the BWR vessels have ratios of approximately 15 and 20 (Table 4). The use of these coefficients results in low values of J_{applied} ; however, for the flaw depths of interest, the difference is negligible.

The total load stress intensity factor (K_{ITotal}) is the sum of K_{Ip} and K_{It} . K_{ITotal} is used to calculate the effective flaw depth (a_e) for small-scale yielding from the relation [3]

$$a_e = a + (1/6 \pi) [(K_{ITotal})/\sigma_{\text{yield}}]^2. \quad (7)$$

The coefficient of 1/6 in Eq. (7) is appropriate for plane strain constraint conditions that are associated with deep-flaw geometries. For shallow flaws, the plastic zone size would increase due to a relaxation of crack-tip constraint. Incorporating shallow-flaw effects into these calculations would necessitate modifications to Eq. (7).

The purpose of the successive calculations, illustrated in Fig. 4, is to include the variation of the geometry factor in the expression for K_{ITotal} . The effect of the plastic zone correction on K_{ITotal} is determined by calculating K_{ITotal} three times, using the updated effective flaw depth in each successive calculation. A value of 65 ksi was assumed for the yield stress (σ_{yield}).

Step II:

The J_{applied} due to K_{ITotal} for small-scale yielding is given by Eq. (8) [3],

$$J_{\text{applied}}(\tau) = 1000 (K_{ITotal})^2 / (E/(1 - \nu^2)), \quad (8)$$

Figure 4. Flow chart logic for calculating $J_{applied}$ time history

Analysis

where

E = Modulus of elasticity
 ν = Poisson's ratio,

with units expressed as follows:

$$\begin{aligned} K_{ITotal} &= \text{ksi}\sqrt{\text{in.}} \\ E &= \text{ksi} \\ J_{\text{applied}}(\tau) &= \text{in.-lb/in.}^2 \end{aligned}$$

The generation of the $J_{\text{applied}}(\tau)$ curves was a laborious procedure, because presently there is no single software program that integrates this methodology. The following three pieces of software were required to determine each $[\tau, J_{\text{applied}}(\tau)]$ pair: (1) FAVOR or VISA-II to generate the K_{It} for semielliptical flaws (aspect ratio of 6:1); (2) a program to curve fit the K_{It} calculations as a function of a/t ratio; and (3) a program to integrate the entire methodology shown in Fig. 4.

5.1.2 Generation of J_R Time History

A J_R time history is generated by substituting values of CVN and the temperature-time history corresponding to the original crack tip into the applicable J_R correlation, while keeping $(\Delta a) = 0.10$ in.

5.1.3 Determination of Limiting Values

The J_R time history at $\Delta a = 0.10$ in. is superimposed on the J_{applied} time history. The minimum value of CVN satisfying acceptance criterion 1 is the value of CVN that, when substituted into the appropriate J_R correlation, results in the J_R time history curve approaching a point of tangency with the J_{applied} curve (for example, see Fig. 6). The transient time at which the two curves approach tangency is the critical transient time. This is also assumed to be the critical transient time at which acceptance criterion 2 should be evaluated. This assumption is discussed in more detail in Sect. 5.2.3.

In many analyses, no point of tangency occurs for the minimum value of CVN (or maximum value of neutron fluence) for which the J_R model is valid. In these cases, it can be concluded that the limiting value of CVN or neutron fluence satisfying acceptance criterion 1 would be less (or for the case of neutron fluence, greater) than that for which the correlation is assumed to be valid.

5.2 Satisfying Acceptance Criterion 2

Satisfying acceptance criterion 2 requires a determination that flaw growth would be stable under the conditions as defined by Eq. (2). This criterion is satisfied if the slope of

the material resistance curve (J_R curve) is greater than the slope of the J_{applied} vs crack extension curve at the point where the two curves intersect. This involves a comparison of the two curves at the critical transient time.

For level A and B conditions, $SF = 1.15$ and 1.25 are used as multipliers on the accumulation pressure when evaluating acceptance criteria 1 and 2, respectively. Therefore, the limiting value of CVN or neutron fluence satisfying acceptance criterion 1 does not necessarily satisfy acceptance criterion 2.

5.2.1 Generation of J_{applied} —Crack Extension (Δa) Curve

The flow chart logic for this methodology is illustrated in Fig. 5 and is explained below.

The $J_{\text{applied}}-(\Delta a)$ curves are generated for a series of flaw depths corresponding to increasing amounts of crack extension (Δa) at the critical transient time.

Calculation of the $J_{\text{applied}}-(\Delta a)$ curve consists of the same steps as previously explained in Sect. 5.1.1.

For a specified crack depth ($a = a_0 + \Delta a$), a small-scale yield adjusted value of J_{applied} is determined based on an effective crack depth (a_e).

5.2.2 Generation of J_R —Crack Extension (Δa) Curve

A J_R -crack extension (Δa) curve is generated for a series of flaw depths corresponding to increasing amounts of crack extension (Δa). The curve is evaluated at the critical transient time and corresponding crack tip temperature at the original crack tip location.

The analyses in this study used the temperature at the initial crack tip (a_0) at the critical transient time for all through wall locations evaluated. A more rigorous approach would include the through wall temperature variation associated with Δa at the critical transient time.

5.2.3 Determination of Limiting Values

The minimum value of CVN (or maximum value of neutron fluence) satisfying acceptance criterion 2 is the lowest value of CVN that, when substituted into the appropriate J_R correlation, results in a J_R -crack extension (Δa) curve that has a greater slope than the $J_{\text{applied}}-(\Delta a)$ curve at the point of intersection. Both curves are evaluated at the critical transient time as determined in Sect. 5.1.3. For level A and B conditions, $SF = 1.25$ was used as a multiplier on the accumulation pressure, whereas for level C condition, $SF = 1.0$ was used.

For level A and B conditions, it is possible that the limiting value of CVN (or neutron fluence) that satisfies acceptance criterion 1 does not satisfy acceptance criterion 2. For example, Fig. 6 illustrates that a CVN of 39 ft-lb satisfies acceptance criterion 1 for an axially oriented flaw in the PWR 1 vessel geometry using the Linde 80 weld (Charpy J_R model). The critical transient time is 48 min. Figure 7 illustrates the results of an acceptance criterion 2 analysis performed at the critical transient time. The J_R curve corresponding to the CVN of 39 ft-lb that satisfies acceptance criterion 1 (Fig. 6) does not intersect the J_{applied} curve with a safety factor of 1.25. A CVN of 41 ft-lb is required to satisfy acceptance criterion 2.

To examine the assumption that the critical transient time determined in the acceptance criterion 1 analysis is also the critical time at which the acceptance criterion 2 analysis should be performed, analyses were performed at other transient times. Figure 8 shows the results of an acceptance

criterion 2 analysis for a CVN value of 41 ft-lb at the critical transient time of 48 min and at earlier transient times. As transient time increases, approaching the critical transient time of 48 min, the degree to which acceptance criterion 2 is satisfied decreases. Figure 9 illustrates the results at the critical transient time of 48 min and at later transient times. As the transient time increases beyond the critical transient time of 48 min, the degree to which acceptance criterion 2 is satisfied increases. Therefore, for this case, the critical times in the transient for satisfying criteria 1 and 2 are the same. The assumption that the critical transient time determined in the acceptance criterion 1 analysis is also the critical transient time for performing the acceptance criterion 2 analysis is used throughout this study. This assumption is also examined for the low-toughness plate J_R model in Sect. 6.1. Nevertheless, these calculations do not constitute a proof that such will be the case for all transient, vessel, and J_R model combinations.

Figure 5. Flow chart logic for calculating $J_{applied}$ -crack extension (Δa) curve

Figure 6. PWR: level A and B conditions; limiting values of CVN required to satisfy acceptance criterion 1 for PWR 1, PWR 2, and PWR 3 for axially oriented flaws, Linde 80 weld (Charpy model)

Figure 7. PWR: level A and B conditions; limiting value of CVN required to satisfy acceptance criteria 1 and 2 for PWR 1 axially oriented flaws, Linde 80 weld (Charpy model)

Figure 8. PWR 1: level A and B conditions; Linde 80 weld (Charpy model); results of acceptance criterion 2 analysis for CVN = 41 ft-lb at critical transient time (48 min) and earlier transient times

Figure 9. PWR 1: level A and B conditions; Linde 80 weld (Charpy model); results of acceptance criterion 2 analysis for CVN = 41 ft-lb at critical transient time (48 min) and later transient times

6 Analysis Results

6.1 PWR: Level A and B

Table 5 summarizes results of the analyses for vessels PWR 1-4 for level A and B conditions. The results are presented in the form of limiting values of CVN and neutron fluence for the various combinations of vessel geometries, flaw orientations, acceptance criterion, and J_R models. The table also indexes the figure numbers that illustrate the results of the applicable analysis.

As discussed in Sect. 5.1.1, detailed analyses were performed to determine the J_{applied} time history. For level A and B conditions, the loading is produced by a thermal transient characterized by a constant cooldown rate (100°F/h) and a constant pressure. The thermally induced stress intensity factor (K_{It}) at any radial location in the vessel wall, calculated by FAVOR or VISA-II, initially increases with time. As the time rate of change of temperature diminishes, K_{It} approaches a constant maximum value.

Figure 6 illustrates the J_{applied} time histories at the location of maximum flaw depth for an axially oriented semielliptical (6 to 1) inside surface flaw with maximum crack depth of $a = (0.25t + 0.1)$ in. for the PWR 1-3 vessel geometries. The loading at $t = 0$ is pressure induced. The maximum values of the stress intensity factor associated with the radial thermal gradient (K_{It}) calculated by FAVOR and VISA-II agree well with those predicted by the procedure suggested in Code Case N-512. As shown in Fig. 6, the maximum values of J_{applied} were not reached until approximately 100, 160, and 120 min into the transient for PWR 1-3, respectively. During the time required to reach the maximum load, the temperature-dependent material resistances are also increasing.

The pressure-induced load is proportional to the vessel internal radius-to-wall thickness ratio (R/t), whereas the thermally induced loading increases with increasing wall thickness. As shown in Fig. 6, PWR 1 has the highest pressure-induced J_{applied} , since it has the largest (R/t) ratio. The PWR 2 geometry has the highest thermally induced J_{applied} since it has the thickest vessel wall (see Table 4).

In Fig. 6 the J_R time histories obtained from the Linde 80 weld (Charpy J_R model) are superimposed on their respective J_{applied} time histories for PWR 1-3. The J_R time histories correspond to the minimum acceptable values of CVN satisfying acceptance criterion 1. The minimum acceptable value of CVN, when substituted into the J_R correlation, results in the J_R time history curve approaching tangency with the J_{applied} time history curve. The critical transient times, i.e., the times at which the curves approach tangency for PWR 1-3 are approximately 48, 72, and 48 min, respectively. The minimum acceptable values of

CVN satisfying acceptance criterion 1 for PWR 1-3 are 39, 37, and 33 ft-lb, respectively.

Figure 7 shows the J_{applied} -crack extension (Δa) curves and the J_R curves obtained from the Linde 80 weld (Charpy J_R model) at the critical transient time of 48 min for an axially oriented flaw in PWR 1. The two J_{applied} -crack extension (Δa) curves are based on safety factors of 1.15 and 1.25 for the accumulation pressure. The CVN value of 39 ft-lb satisfies acceptance criterion 1 but not acceptance criterion 2. To satisfy acceptance criterion 2, the slope of the J_R curve must be greater than the slope of the J_{applied} curve ($SF = 1.25$) at the point of intersection. A CVN value of 41 ft-lb is the minimum acceptable value that satisfies acceptance criteria 1 and 2 for PWR 1. As a matter of interest, application of the steady-state equation to predict the thermally induced stress intensity factor results in a minimum acceptable CVN of 47 ft-lb for PWR 1. Similarly, Figs. 10 and 11 indicate that CVN values of 37 ft-lb and 34 ft-lb are the minimum acceptable values of CVN for PWR 2 and PWR 3, respectively.

Figure 12 depicts the J_{applied} time histories calculated for a circumferentially oriented semielliptical (6 to 1) inside surface flaws at a crack depth of $a = (0.25t + 0.1)$ in. for the PWR 1-3 vessels. The J_R time histories obtained from the Linde 80 weld (Charpy J_R model) corresponding to a CVN value of 22 ft-lb are superimposed on the J_{applied} time histories. The CVN in the circumferential orientation is considered to be 65% of that in the longitudinal orientation. A CVN value of 22 ft-lb is the minimum value in the circumferential orientation for which the J_R correlation is assumed to be valid. Acceptance criteria 1 and 2 are easily satisfied for the CVN value of 22 ft-lb. A figure illustrating the results of the analysis for acceptance criterion 2 is not included. It can be concluded that the minimum acceptable value of CVN is less than 22 ft-lb.

Figures 13 and 14 illustrate the results of similar analyses for an axially oriented flaw in the PWR 4 vessel obtained by applying the low-toughness plate J_R model. The limiting value of CVN is 51 ft-lb. As discussed in Sect. 4, the data base used to generate the J_R correlation was established for the weak orientation. The CVN value and the J - P correlation for the axially oriented flaws (strong, I-T orientation) is conservatively assumed to be the same as those for the circumferentially oriented flaws (weak, T-L orientation).

It was assumed herein that the critical transient time determined in the acceptance criterion 1 analysis is also the critical transient time for performing the acceptance criterion 2 analysis. The validity of the assumption was examined for the low-toughness plate J_R model. Figure 15 shows the results of an acceptance criterion 2 analysis for a CVN value of 51 ft-lb at the critical transient time of 48 min and at earlier transient times. As transient time increases, approaching the critical transient time of 48 min, the margin

Table 5. Limiting values of CVN and neutron fluence for PWRs: levels A and B

Figure	Geometry	Flaw orientation	Acceptance criterion	J _R model	Limiting CVN (ft-lb)
6	PWR 1-3	Axial	1	Linde 80 weld (Charpy)	39, 37, 33
7	PWR 1	Axial	2	Linde 80 weld (Charpy)	41
10	PWR 2	Axial	2	Linde 80 weld (Charpy)	37
11	PWR 3	Axial	2	Linde 80 weld (Charpy)	34
12	PWR 1-3	Circum	1	Linde 80 weld (Charpy)	22*
13	PWR 4	Axial	1	low-toughness plate	48
14	PWR 4	Axial	2	low-toughness plate	51
17	PWR 4	Circum	1	low-toughness plate	25**
18	PWR 4	Circum	2	low-toughness plate	25**
					Limiting fluence [†] (10 ¹⁹ n/cm ²)
19	PWR 1-3	Axial	1	Linde 80 weld (copper-fluence)	1.7, 1.9, 2.75
20	PWR 1	Axial	2	Linde 80 weld (copper-fluence)	1.6
21	PWR 2	Axial	2	Linde 80 weld (copper-fluence)	1.9
22	PWR 3	Axial	2	Linde 80 weld (copper-fluence)	2.5
23	PWR 1-3	Circum	1	Linde 80 weld (copper-fluence)	3.6‡

*Actual limiting value unknown; 22 ft-lb is minimum value of CVN for which the J_R model is assumed to be valid for circumferentially oriented flaws.

**Actual limiting value unknown; 25 ft-lb is minimum value of CVN for which the J_R model is assumed to be valid.

†Analyses assumed 0.35% copper concentration (see Fig. 24 for sensitivity of limiting value of fluence with respect to copper).

‡Actual limiting value unknown; 3.6×10^{19} n/cm² is the maximum value of fluence for which the J_R model is assumed to be valid.

by which acceptance criterion 2 is satisfied decreases. Figure 16 illustrates the results at the critical transient time of 48 min and at later transient times. As transient time increases beyond the critical transient time of 48 min, the margin by which acceptance criterion 2 is satisfied increases. Therefore, for this case, the critical times in the transient for satisfying criteria 1 and 2 are the same.

Figures 17 and 18 show the results of similar analyses for a circumferentially oriented flaw in PWR 4 obtained by applying the low-toughness plate J_R model. It can be concluded that the minimum acceptable value of CVN is less than 25 ft-lb.

In Fig. 19, the J_R time histories obtained from the Linde 80 weld (copper-fluence J_R model) are superimposed on the J_{applied} time histories for axially oriented flaws in PWR 1-3. These J_R curves correspond to the maximum acceptable values of neutron fluence satisfying acceptance criterion 1. The maximum acceptable value of neutron fluence, when substituted into the J_R correlation with a specified value of copper, results in the J_R time history curve approaching tangency with the J_{applied} curve. It should be noted that a value for copper of 0.35 wt % was assumed in these analyses. The maximum acceptable values of fluence satisfying acceptance criterion 1 for PWR 1-3 are 1.7, 1.9,

and 2.75×10^{19} n/cm², respectively. Figure 20 illustrates that for PWR 1, a maximum fluence of 1.6×10^{19} n/cm² satisfies acceptance criteria 1 and 2. Similarly, Figs. 21 and 22 show that the maximum acceptable values of neutron fluence for PWR 2 and PWR 3 are 1.9 and 2.5×10^{19} n/cm², respectively.

In Fig. 23, the J_R time histories obtained from the Linde 80 weld (copper-fluence J_R model) for a neutron fluence of 3.6×10^{19} n/cm² are superimposed on the J_{applied} time histories for circumferentially oriented flaws in PWR 1-3. This is the maximum value of neutron fluence for which the J_R model is considered valid. Acceptance criterion 1 is easily satisfied for level A and B conditions. Acceptance criterion 2 is also satisfied (figure not included). Therefore, it can be concluded that the maximum acceptable value of fluence is greater than 3.6×10^{19} n/cm² to satisfy acceptance criteria.

Figure 24 illustrates the sensitivity of the maximum acceptable value of neutron fluence satisfying the acceptance criterion with respect to copper for the PWR 1 limiting case. Reducing the copper content from 0.35 wt % to ~0.25 wt % approximately doubles the acceptable neutron fluence.

Figure 10. PWR: level A and B conditions; limiting value of CVN required to satisfy acceptance criteria 1 and 2 for PWR 2 axially oriented flaws, Linde 80 weld (Charpy model)

Figure 11. PWR: level A and B conditions; limiting value of CVN required to satisfy acceptance criteria 1 and 2 for PWR 3 axially oriented flaws, Linde 80 weld (Charpy model)

Figure 12. PWR: level A and B conditions; limiting value of CVN required to satisfy acceptance criterion 1 for PWR 1, PWR 2, and PWR 3 for circumferentially oriented flaws, Linde 80 weld (Charpy model)

Figure 13. PWR: level A and B conditions; limiting value of CVN required to satisfy acceptance criterion 1 for PWR 4 for axially oriented flaws, low-toughness plate model

Figure 14. PWR: level A and B conditions; limiting value of CVN required to satisfy acceptance criteria 1 and 2 for PWR 4 for axially oriented flaws, low-toughness plate model

Figure 15. PWR 4: level A and B conditions; low-toughness plate model; results of acceptance criterion 2 analysis for CVN = 51 ft-lb at critical transient time (48 min) and earlier transient times

Figure 16. PWR 4: level A and B conditions; low-toughness plate model; results of acceptance criterion 2 analysis for CVN = 51 ft-lb at critical transient time (48 min) and later transient times

Figure 17. PWR: level A and B conditions; limiting value of CVN required to satisfy acceptance criterion 1 for PWR 4 for circumferentially oriented flaws, low-toughness plate model

Figure 18. PWR: level A and B conditions; limiting value of CVN required to satisfy acceptance criteria 1 and 2 for PWR 4 for circumferentially oriented flaws, low-toughness plate model

Figure 19. PWR: level A and B conditions; limiting values of neutron fluence required to satisfy acceptance criterion 1 for PWR 1, PWR 2, and PWR 3 for axially oriented flaws, Linde 80 weld (copper-fluence model)

Figure 20. PWR: level A and B conditions; limiting value of neutron fluence required to satisfy acceptance criteria 1 and 2 for PWR 1 axially oriented flaws, Linde 80 weld (copper-fluence model)

Figure 21. PWR: level A and B conditions; limiting values of neutron fluence required to satisfy acceptance criteria 1 and 2 for PWR 2 axially oriented flaws, Linde 80 weld (copper-fluence model)

Figure 22. PWR: level A and B conditions; limiting value of neutron fluence required to satisfy acceptance criteria 1 and 2 for PWR 3 axially oriented flaws, Linde 80 weld (copper-fluence model)

Figure 23. PWR: level A and B conditions; limiting values of neutron fluence required to satisfy acceptance criterion 1 for PWR 1, PWR 2, and PWR 3 for circumferentially oriented flaws, Linde 80 weld (copper-fluence model)

Figure 24. PWR: level A and B conditions; limiting value of neutron fluence as a function of copper content for PWR 1 axially oriented flaws, Linde 80 weld (copper-fluence model)

6.2 PWR: Level C

Table 6 summarizes results of the analyses for PWR 1–4 vessels for the level C condition. Results are presented in the form of limiting values of CVN and neutron fluence for the various combinations of vessel geometries, flaw orientations, acceptance criterion, and J_R models. The table also indexes the figure numbers that illustrate the results of the applicable analysis.

A transient stress analysis was performed for the specified level C transient to incorporate the time dependence of the thermally induced load. The more detailed methodology used for the Level A and B analyses was utilized in this study.

In Fig. 25, the J_R time histories obtained from the Linde 80 weld (Charpy J_R model) for a CVN of 33 ft-lb are superimposed on the J_{applied} time histories for axially oriented flaws in PWR 1–3. This is the minimum value of CVN for which the J_R model is considered valid. Acceptance criterion 1 is easily satisfied. Acceptance criterion 2 is also satisfied for a CVN of 33 ft-lb (figure not included). It can be concluded that the minimum acceptable value of CVN is less than 33 ft-lb.

Figure 26 illustrates that the minimum acceptable value of CVN required to satisfy acceptance criterion 1 is less than 22 ft-lb for circumferentially oriented flaws. Acceptance criterion 2 is also satisfied for a CVN of 22 ft-lb (figure not included). It can be concluded that the minimum acceptable value of CVN is less than 22 ft-lb.

Figures 27–30 illustrate that the minimum acceptable values of CVN obtained by applying the low-toughness-plate J_R model to PWR 4 are 34 and 28 ft-lb for axially and circumferentially oriented flaws, respectively. The CVN value and the J-R correlation for the axially oriented flaws (strong, L-T orientation) is conservatively assumed to be the same as those for the circumferentially oriented flaws (weak, T-L orientation).

In Fig. 31, the J_R time histories obtained from the Linde 80 weld (copper-fluence J_R model) for a neutron fluence of 3.6×10^{19} n/cm² are superimposed on the J_{applied} time histories for axially oriented flaws in PWR 1–3. Acceptance criterion 1 is satisfied for level C condition. Acceptance criterion 2 is also satisfied (figure not included). It can be concluded that the maximum acceptable value of fluence is greater than 3.6×10^{19} n/cm². Figure 32 illustrates similar results for circumferentially oriented flaws.

6.3 PWR: ATWS Transients

Anticipated-transients-without-SCRAM (ATWS) were considered in the category of a level C condition. The PWR vessel geometries, constant pressures [8] and temperatures

used in the analyses are specified in Table 7. J_{applied} and J_R are both invariant with respect to time; therefore, the generation of time histories is not required.

Table 8 summarizes results of the analyses for PWR 1, 4, and 5 vessels. The results are presented in the form of limiting values of CVN for the various combinations of vessel geometries, flaw orientations, acceptance criteria, and J_R models. The table also indexes the figure numbers that illustrate the results of the applicable analysis.

In Figs. 33 and 34, the J_R curves obtained from the Linde 80 weld (Charpy J_R model) are superimposed on the $J_{\text{applied}}-(\Delta a)$ curves for axially and circumferentially oriented flaws in vessels PWR 1, 4, and 5. It can be concluded that the minimum acceptable values of CVN are less than 33 and 22 ft-lb for axially and circumferentially oriented flaws, respectively.

In Fig. 35, the J_R curves obtained from the Linde 80 weld (copper-fluence model) are superimposed on the $J_{\text{applied}}-(\Delta a)$ curves for axially oriented flaws in vessel PWR 1, 4, and 5. The J_R curves correspond to a neutron fluence of 3.6×10^{19} n/cm². Because the same J_R curves are used for circumferentially oriented flaws, it follows that the maximum acceptable neutron fluence is greater than 3.6×10^{19} n/cm² for both axially and circumferentially oriented flaws.

In Figs. 36 and 37, the J_R curves obtained from the low-toughness plate J_R correlation are superimposed on the $J_{\text{applied}}-(\Delta a)$ curves for axially and circumferentially oriented flaws in the limiting vessel PWR 4, respectively. It can be concluded that the minimum acceptable values of CVN are 33 and 28 ft-lb for axially and circumferentially oriented flaws, respectively.

6.4 BWR: Level A and B Conditions

Table 9 summarizes results of the analyses for BWR 1–2 vessels for level A and B conditions. The results are presented in the form of limiting values of CVN for the various combinations of vessel geometries, flaw orientations, acceptance criterion, and J_R models. The table also indexes the figure numbers that illustrate the results of the applicable analysis.

In Fig. 38, the J_R time histories obtained from the Linde 80 weld (Charpy J_R model) for a CVN of 33 ft-lb are superimposed on the J_{applied} time histories for axially oriented flaws in BWR 1–2. Acceptance criterion 1 is easily satisfied for level A and B conditions. In Fig. 38, the J_R time histories for circumferentially oriented flaws corresponding to a value of CVN of 22 ft-lb are also superimposed on the J_{applied} time histories for axially oriented flaws. The J_{applied} time histories for axially oriented flaws are greater

Table 6. Limiting values of CVN and neutron fluence for PWRs: level C

Figure	Geometry	Flaw orientation	Acceptance criterion	J _R model	Limiting CVN (ft-lb)
25	PWR 1-3	Axial	1	Linde 80 weld (Charpy)	33*
26	PWR 1-3	Circum	1	Linde 80 weld (Charpy)	22**
27	PWR 4	Axial	1	low-toughness plate	34
28	PWR 4	Axial	2	low-toughness plate	34
29	PWR 4	Circum	1	low-toughness plate	28
30	PWR 4	Circum	2	low-toughness plate	28
					Limiting fluence [†] (10 ¹⁹ n/cm ²)
31	PWR 1-3	Axial	1	Linde 80 weld (copper-fluence)	3.6‡
32	PWR 1-3	Circum	1	Linde 80 weld (copper-fluence)	3.6‡

*Actual limiting value unknown; 33 ft-lb is minimum value of CVN for which the J_R model is assumed to be valid.

**Actual limiting value unknown; 22 ft-lb is minimum value of CVN for which the J_R model is assumed to be valid for circumferentially oriented flaws.

†Analyses assumed 0.35% copper concentration.

‡Actual limiting value unknown; 3.6×10^{19} n/cm² is the maximum value of fluence for which the J_R model is assumed to be valid.

Table 7. Pressures and temperatures for ATWS transients

Vessel geometry	Pressure (ksi)	Inlet temperature (°F)*
PWR 1	3.378	540
PWR 4	4.121	532
PWR 5	3.789	550

*Constant coolant and vessel temperature

Table 8. Limiting values of CVN and neutron fluence for PWRs: ATWS transients

Figure	Geometry	Flaw orientation	Acceptance criteria	J _R model	Limiting CVN (ft-lb)
33	PWR 1, 4, 5	Axial	1 and 2	Linde 80 weld (Charpy)	33*
34	PWR 1, 4, 5	Circum	1 and 2	Linde 80 weld (Charpy)	22**
36	PWR 4	Axial	1 and 2	low-toughness plate	33
37	PWR 4	Circum	1 and 2	low-toughness plate	28
					Limiting fluence [†] (10 ¹⁹ n/cm ²)
35	PWR 1, 4, 5	Axial	1 and 2	Linde 80 weld (copper-fluence)	3.6‡

*Actual limiting value unknown; 33 ft-lb is minimum value of CVN for which the J_R model is assumed to be valid.

**Actual limiting value unknown; 22 ft-lb is minimum value of CVN for which the J_R model is assumed to be valid for circumferentially oriented flaws.

†Analyses assumed 0.35% copper concentration.

‡Actual limiting value unknown; 3.6×10^{19} n/cm² is the maximum value of fluence for which the J_R model is assumed to be valid.

Table 9. Limiting values of CVN for BWRs: levels A and B

Figure	Geometry	Flaw orientation	Acceptance criterion	J _R model	Limiting CVN (ft-lb)
38	BWR 1-2	Axial	1	Linde 80 weld (Charpy)	33*
38	BWR 1-2	Circum	1	Linde 80 weld (Charpy)	22**
39	BWR 1-2	Axial	1	low-toughness plate	31, 28
40	BWR 1	Axial	2	low-toughness plate	36
41	BWR 2	Axial	2	low-toughness plate	31
42	BWR 1-2	Circum	1	low-toughness plate	25†
43	BWR 1-2	Axial	1	Generic weld	33*
43	BWR 1-2	Circum	1	Generic weld	22**

*Actual limiting value unknown; 33 ft-lb is minimum value of CVN for which the J_R model is assumed to be valid.

**Actual limiting value unknown; 22 ft-lb is minimum value of CVN for which the J_R model is assumed to be valid for circumferentially oriented flaws.

†Actual limiting value unknown; 25 ft-lb is the minimum value of CVN for which the J_R model is assumed to be valid.

Figure 25. PWR: level C condition; limiting values of CVN required to satisfy acceptance criterion 1 for PWR 1, PWR 2, and PWR 3 for axially oriented flaws, Linde 80 weld (Charpy model)

Figure 26. PWR: level C condition; limiting values of CVN required to satisfy acceptance criterion 1 for PWR 1, PWR 2, and PWR 3 for circumferentially oriented flaws, Linde 80 weld (Charpy model)

Figure 27. PWR: level C condition; limiting value of CVN required to satisfy acceptance criterion 1 for PWR 4 for axially oriented flaws, low-toughness plate model

Figure 28. PWR: level C condition; limiting value of CVN required to satisfy acceptance criteria 1 and 2 for PWR 4 for axially oriented flaws, low-toughness plate model

Figure 29. PWR: level C condition; limiting value of CVN required to satisfy acceptance criterion 1 for PWR 4 for circumferentially oriented flaws, low-toughness plate model

Figure 30. PWR: level C conditions; limiting value of CVN required to satisfy acceptance criteria 1 and 2 for PWR 4 for circumferentially oriented flaws, low-toughness plate model

Figure 31. PWR: level C condition; limiting values of neutron fluence required to satisfy acceptance criterion 1 for PWR 1, PWR 2, and PWR 3 for axially oriented flaws, Linde 80 weld (copper-fluence model)

Figure 32. PWR: level C condition; limiting values of neutron fluence required to satisfy acceptance criterion 1 for PWR 1, PWR 2, and PWR 3 for circumferentially oriented flaws, Linde 80 weld (copper-fluence model)

Figure 33. PWR: ATWS transient; limiting values of CVN required to satisfy acceptance criteria 1 and 2 for PWR 1,4, and 5 for axially oriented flaws, Linde 80 weld (Charpy model)

Figure 34. PWR: ATWS transient; limiting values of CVN required to satisfy acceptance criteria 1 and 2 for PWR 1,4, and 5 for circumferentially oriented flaws, Linde 80 weld (Charpy model)

Figure 35. PWR: ATWS transient; limiting values of neutron fluence required to satisfy acceptance criteria 1 and 2 for PWR 1, 4, and 5 for axially oriented flaws, Linde 80 weld (copper-fluence model)

Figure 36. PWR: ATWS transient; limiting value of CVN required to satisfy acceptance criteria 1 and 2 for PWR 4 for axially oriented flaws, low-toughness plate model

Figure 37. PWR: ATWS transient: limiting value of CVN required to satisfy acceptance criteria 1 and 2 for PWR 4 for circumferentially oriented flaws, low-toughness plate model

Figure 38. BWR: level A and B conditions; limiting values of CVN required to satisfy acceptance criterion 1 for BWR 1 and BWR 2 for axially and circumferentially oriented flaws, Linde 80 weld (Charpy model)

than those for circumferentially oriented flaws. Because no tangency occurs between the J_{applied} time histories for axial flaws and the J_R time histories for circumferential flaws, it follows that acceptance criterion 1 is satisfied for circumferentially oriented flaws. Acceptance criterion 2 is also easily satisfied for both flaw orientations (figures not included). It can be concluded that the minimum acceptable values of CVN are less than 33 and 22 ft-lb for axially and circumferentially oriented flaws, respectively.

In Fig. 39, the J_R time histories obtained from the low-toughness plate J_R model are superimposed on the J_{applied} time histories for axially oriented flaws in BWR 1–2. The minimum acceptable values of CVN satisfying acceptance criterion 1 for BWR 1–2 are 31 and 28 ft-lb, respectively. The CVN value of 31 ft-lbs satisfies acceptance criterion 1 for BWR 1, but not acceptance criterion 2. A CVN value of 36 ft-lbs is the minimum acceptable value that satisfies acceptance criterion 2 for BWR 1, as illustrated in Fig. 40. Similarly, the CVN value of 28 ft-lb satisfying acceptance criterion 1 for BWR 2 does not satisfy acceptance criterion 2. A CVN value of 31 ft-lb is the minimum acceptable value that satisfies acceptance criterion 2 for BWR 2, as illustrated in Fig. 41.

Figure 42 illustrates the J_R time histories obtained from the low-toughness plate J_R model for a CVN of 25 ft-lb superimposed on the J_{applied} time histories for circumferentially oriented flaws in BWR 1–2. This is the minimum value of CVN for which this J_R correlation is assumed to be valid. Acceptance criterion 1 is easily satisfied. Acceptance criterion 2 is also easily satisfied for both flaw orientations (figure not included).

Figure 43 illustrates similar results for axially and circumferentially oriented flaws in BWR 1–2 using the generic weld J_R model.

6.5 BWR: Level C Condition

Table 10 summarizes results of the analyses for BWR 1–2 vessels for the level C condition. The results are presented in the form of limiting values of CVN for the various combinations of vessel geometries, flaw orientations, acceptance criterion, and J_R models. The table also indexes the figure numbers that illustrate the results of the applicable analysis.

Figure 44 illustrates the J_{applied} time histories for axially oriented semielliptical (6 to 1) inside surface flaws at a crack depth of $a = (0.10t + 0.1)$ in. for the BWR 1 and BWR 2 vessel geometries for service level C (transient 1; see Fig. 2) condition. The J_R time histories obtained from the Linde 80 weld (Charpy model) for axially and circumferentially oriented flaws for BWR 1–2 corresponding to a CVN of 33 ft-lb, are superimposed on the J_{applied} time histories. It can be concluded that the limiting values of CVN for axially and circumferentially oriented flaws for BWR 1–2 are less than 33 and 22 ft-lb, respectively.

Figure 45 illustrates similar results for transient 2 (Fig. 3) loading condition.

Figures 46 and 47 illustrate similar results for axially and circumferentially oriented flaws in BWR 1–2 using the low-toughness plate J_R model for transients 1 and 2, respectively.

Figures 48 and 49 illustrate similar results for axially and circumferentially oriented flaws in BWR 1–2 using the generic weld J_R model for transients 1 and 2, respectively.

Table 10. Limiting values of CVN for BWRs: level C

Figure	Geometry	Flaw orientation	Acceptance criterion	J _R model	Limiting CVN (ft-lb)
44	BWR 1-2	Axial	1	Linde 80 weld: (Charpy)	33*
44	BWR 1-2	Circum	1	Linde 80 weld: (Charpy)	22**
45	BWR 1-2	Axial	1	Linde 80 weld: (Charpy)	33*
45	BWR 1-2	Circum	1	Linde 80 weld: (Charpy)	22**
46	BWR 1-2	Axial	1	low-toughness plate	25†
46	BWR 1-2	Circum	1	low-toughness plate	25†
47	BWR 1-2	Axial	1	low-toughness plate	25†
47	BWR 1-2	Circum	1	low-toughness plate	25†
48	BWR 1-2	Axial	1	Generic weld	33*
48	BWR 1-2	Circum	1	Generic weld	22**
49	BWR 1-2	Axial	1	Generic weld	33*
49	BWR 1-2	Circum	1	Generic weld	22**

* Actual limiting value unknown; 33 ft-lb is minimum value of CVN for which the J_R model is assumed to be valid.

** Actual limiting value unknown; 22 ft-lb is minimum value of CVN for which the J_R model is assumed to be valid for circumferentially oriented flaws.

† Actual limiting value unknown; 25 ft-lb is the minimum value of CVN for which J_R model is assumed to be valid.

Figure 39. BWR: level A and B conditions; limiting values of CVN required to satisfy acceptance criterion 1 for BWR 1 and BWR 2 for axially oriented flaws, low-toughness plate model

Figure 40. BWR: level A and B conditions; limiting value of CVN required to satisfy acceptance criteria 1 and 2 for BWR 1 for axially oriented flaws, low-toughness plate model

Figure 41. BWR: level A and B conditions; limiting value of CVN required to satisfy acceptance criteria 1 and 2 for BWR 2 for axially oriented flaws, low-toughness plate model

Figure 42. BWR: level A and B conditions; limiting values of CVN required to satisfy acceptance criterion 1 for BWR 1 and BWR 2 for circumferentially oriented flaws, low-toughness plate model

Figure 43. BWR: level A and B conditions; limiting values of CVN required to satisfy acceptance criterion 1 for BWR 1 and BWR 2 for axially and circumferentially oriented flaws, generic weld model

Figure 44. BWR: level C condition (transient 1); limiting values of CVN required to satisfy acceptance criterion 1 for BWR 1 and BWR 2 for axially and circumferentially oriented flaws, Linde 80 weld (Charpy model)

Figure 45. BWR: level C condition (transient 2); limiting values of CVN required to satisfy acceptance criterion 1 for BWR 1 and BWR 2 for axially and circumferentially oriented flaws, Linde 80 weld (Charpy model)

Figure 46. BWR: level C condition (transient 1); limiting values of CVN required to satisfy acceptance criterion 1 for BWR 1 and BWR 2 for axially and circumferentially oriented flaws, low-toughness plate model

Figure 47. BWR: level C condition (transient 2); limiting values of CVN required to satisfy acceptance criterion 1 for BWR 1 and BWR 2 for axially and circumferentially oriented flaws, low-toughness plate model

Figure 48. BWR: level C condition (transient 1); limiting values of CVN required to satisfy acceptance criterion 1 for BWR 1 and BWR 2 for axially and circumferentially oriented flaws, generic weld model

Figure 49. BWR: level C condition (transient 2); limiting value of CVN required to satisfy acceptance criterion 1 for BWR 1 and BWR 2 for axially and circumferentially oriented flaws, generic weld model

7 Summary of Results

Table 11 summarizes the bounding results of CVN and neutron fluence that satisfy the acceptance criteria for PWR geometries, flaw orientations, and J_R models considered in this study. The most severe limiting cases of CVN and neutron fluence are for axially oriented flaws for level A and B conditions.

orientations, and J_R models considered in this study. In all cases except one (axially oriented flaw for low-toughness plate model), the acceptance criteria were satisfied by the minimum value for which the correlation was assumed to be valid.

Table 12 summarizes the bounding results of CVN that satisfy the acceptance criteria for BWR geometries, flaw

Table 11. Bounding values of CVN and neutron fluence for PWRs

Axially oriented flaws			
Material (J_R model)	Level	Minimum acceptable CVN (ft-lb)	Maximum acceptable neutron fluence* (10^{19} n/cm ²)
Linde 80 weld (Charpy model)	A and B	41	—
Linde 80 Weld (copper-fluence model)	A and B	—	1.6
Low-toughness-plate model	A and B	51	—
Linde 80 Weld (Charpy model)	C	33**	—
Linde 80 Weld (copper-fluence model)	C	—	3.6 [†]
Low-toughness-plate model	C	34	—
Circumferentially oriented flaws			
Material (J_R model)	Level	Minimum acceptable CVN (ft-lb)	Maximum acceptable neutron fluence (10^{19} n/cm ²)
Linde 80 weld (Charpy mode)	A and B	22 [‡]	—
Linde 80 weld (copper-fluence model)	A and B	—	3.6 [†]
Low-toughness-plate model	A and B	25 ^{‡‡}	—
Linde 80 weld (Charpy model)	C	22 [‡]	—
Linde 80 weld (copper-fluence model)	C	—	3.6 [†]
Low-toughness-plate model	C	28	—

* Analyses assumed 0.35 wt % copper concentration. See Fig. 24 for sensitivity of limiting value of fluence with respect to copper for limiting case.

**Actual limiting value unknown; 33 ft-lb is minimum value of CVN for which the J_R model is assumed to be valid.

[†]Actual limiting value unknown; 3.6×10^{19} n/cm² is the maximum value of fluence for which the J_R model is assumed to be valid.

[‡]Actual limiting value unknown; 22 ft-lb is minimum value of CVN for which the J_R model is assumed to be valid for circumferentially oriented flaws.

^{‡‡}Actual limiting value unknown; 25 ft-lb is the minimum value of CVN for which the J_R model is assumed to be valid.

Table 12. Bounding Values of CVN for BWRs**Axially Oriented Flaws**

Material (J_R model)	Level	Minimum acceptable CVN (ft-lb)
Linde 80 weld (Charpy model)	A and B	33*
Generic weld model	A and B	33*
Low-toughness-plate model	A and B	36
Linde 80 weld (Charpy model)	C	33*
Generic weld model	C	33*
Low-toughness-plate model	C	25**

Circumferentially Oriented Flaws

Material (J_R model)	Level	Minimum acceptable CVN (ft-lb)
Linde 80 weld (Charpy model)	A and B	22 [†]
Generic weld model	A and B	22 [†]
Low-toughness-plate model	A and B	25**
Linde 80 weld (Charpy model)	C	22 [†]
Generic weld model	C	22 [†]
Low-toughness-plate model	C	25**

* Actual limiting value unknown; 33 ft-lb is the minimum value of CVN for which the J_R model is assumed to be valid.

** Actual limiting value unknown; 25 ft-lb is the minimum value of CVN for which the J_R model is assumed to be valid.

[†] Actual limiting value unknown; 22 ft-lb is the minimum value of CVN for which the J_R model is assumed to be valid for circumferentially oriented flaws.

8 Conclusions and Recommendations

Results presented herein indicate that less severe limitations on values of CVN and neutron fluence are calculated when time-dependence of the J_{applied} and J_R models are incorporated into the analyses. Some additional factors that should be addressed in future analyses include the following:

- Does the temperature at the crack tip remain on the upper-shelf during the transient?
- Are flaw sizes smaller than those analyzed in this study (0.25t for level A and B conditions and 0.10t for level C condition) more limiting?
- Are the critical transient times for satisfying acceptance criteria 1 and 2 the same for the combination of vessel, transient, and J_R model being evaluated?
- The through-wall temperature variation at the assumed critical transient time should be incorporated into acceptance criterion 2 calculation of J_R curve. The analyses in this study used the temperature at the original crack tip for all through-wall locations evaluated.
- For shallow flaws, the plastic zone size would increase due to a relaxation of crack-tip constraint. Incorporating shallow-flaw effects into these calculations would necessitate modifications to Eq. (7).

It is anticipated that software incorporating the methodologies used in this study will be integrated into the FAVOR computer program.

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BIBLIOGRAPHIC DATA SHEET

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1. REPORT NUMBER
(Assigned by NRC. Add Vol., Supp., Rev.,
and Addendum Numbers, if any.)

NUREG/CR-6023
ORNL/TM-12340

2. TITLE AND SUBTITLE

Generic Analysis for Evaluation of Low Charpy Upper-Shelf
Energy Effects on Safety Margins Against Fracture of Reactor
Pressure Vessel Materials

3. DATE REPORT PUBLISHED

MONTH YEAR

July 1993

4. FIN OR GRANT NUMBER

B0119

5. AUTHOR(S)

T. L. Dickson

6. TYPE OF REPORT

Technical

7. PERIOD COVERED (Inclusive Dates)

8. PERFORMING ORGANIZATION - NAME AND ADDRESS (If NRC, provide U.S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)

Oak Ridge National Laboratory
Oak Ridge, TN 37831-6285

9. SPONSORING ORGANIZATION - NAME AND ADDRESS (If NRC, type "Same as above"; if contractor, provide NRC Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address.)

Division of Engineering
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555-0001

10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

Appendix G to 10 CFR Part 50 requires that reactor pressure vessel beltline materials maintain Charpy upper-shelf energies of no less than 50 ft-lb during the plant operating life, unless it is demonstrated in a manner approved by the Nuclear Regulatory Commission (NRC), that lower values of Charpy upper-shelf energy provide margins of safety against fracture equivalent to those in Appendix G to Section XI of the ASME Code.

Analyses based on acceptance criteria and analysis methods adopted in the ASME Code Case N-512 are described herein. Additional information on material properties was provided by the NRC, Office of Nuclear Regulatory Research, Materials Engineering Branch. These cases, specified by the NRC, represent generic applications to boiling water reactor and pressurized water reactor vessels. This report is designated as HSST Report No. 140.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)

Charpy
reactor pressure vessel (RPV)
ASME Code Case N-512
low upper-shelf energy
ductile fracture

13. AVAILABILITY STATEMENT

Unlimited

14. SECURITY CLASSIFICATION

(This Page)

Unclassified

(This Report)

Unclassified

15. NUMBER OF PAGES

16. PRICE

END

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10/5/93