Case N-897

Analytical Evaluation Procedures for Axial Flaws in Partial-Penetration Nozzle Welds,

Section XI, Division 1

Inquiry: What provisions may be used for analytical evaluation of an axial flaw in a J-groove weld joint of a partial-penetration nozzle?

Reply: It is the opinion of the Committee that the following provisions may be used for analytical evaluation of an axial flaw in a J-groove weld joint of a partial-penetration nozzle.

1 SCOPE

(a) This Case provides analytical evaluation procedures for an axial indication detected by a nondestructive examination or by evidence of leakage in a partial-penetration nozzle attachment J-groove weld during an in-service inspection. The analytical evaluation may also be applied for a postulated flaw condition where a crack is assumed to remain in the attachment weld following a nozzle repair activity.

(b) The Case may be used for components or piping in either PWR or BWR service.

(c) The applicable nozzle sizes are NPS 3/4 (DN20) to NPS 8 (DN200) and include the following J-groove attachment welds:

- Reactor pressure vessel (RPV) upper head, bottom head, and shell penetrations
- Steam generator and pressurizer head and shell penetrations
- Primary main loop piping instrumentation nozzle penetrations

Figure 1 shows an example of lower head and upper head penetrations for a reactor vessel. The angle of nozzle penetration may vary from perpendicular (≤ 90 deg).

(d) The analytical evaluation procedure describes the details for flaw characterization, flaw growth analysis, and flaw stability analysis to demonstrate structural stability for the evaluation period of operation.

(e) The analytical evaluation may also be applied for a flaw condition where a crack is assumed to remain in the attachment weld following a nozzle repair activity. The flaw that could remain in the original J-groove weld following repair, whether detected or postulated, may be evaluated in accordance with this Case for continued operation without removal of the original weld or penetration nozzle stub. The evaluation procedures may be applied to other similar nozzle repair options where the original J-groove weld remains in service. Example repair options that have been used include the following.

(1) Cap Repair – This form of repair is used if cracking of the nozzle is detected, and the nozzle is not removed from service. A new pressure boundary is created on the outside of the component by welding an integral cap assembly to seal the nozzle penetration. An example of a cap repair for a bottom head penetration is shown in Figure 2.

(2) Half-Nozzle Repair – This form of repair is used if cracking of the nozzle is detected, and the original nozzle is cut and removed from the attachment. A new weld attachment is prepared on the outside surface via a weld pad to accommodate a new J-groove attachment. The original nozzle stub and J-groove weld are not removed. Figure 3 shows an example of a half-nozzle repair.

(3) Embedded Flaw Repair – This form of repair is used if surface cracking is detected in the nozzle or in the J-groove attachment weld, and the original detected flaw is left as-found or is
partially excavated to reduce its size and a weld overlay applied to transform the flaw to an embedded flaw. Figure 4 is an illustration of this type of repair for an RPV vessel head penetration.

(f) This Case is applicable to planar flaws oriented axially with respect to the nozzle axis. This Case is not applicable to circumferentially-oriented flaws.
Figure 1. Example of Partial-Penetration Nozzle and Adjacent Region for Vessel Head

a) Bottom Head Penetration

b) Upper Head Penetration
Figure 2. Example of a Nozzle Cap Repair – Bottom Head Nozzle
Figure 3. Example of a Half-Nozzle Repair—Bottom Head Nozzle
Figure 4. Example of an Embedded Flaw Repair – Upper Head Nozzle
2 PROCEDURE

The procedure to evaluate an axial flaw in a partial-penetration J-groove weld for the applications covered under the scope of this Case is outlined below:

(a) An evaluation period for the analysis shall be established.
(b) The flaw detected or postulated at a J-groove weld shall be characterized in accordance with 3.1.
(c) The loading conditions that are used shall be in accordance with 3.2.
(d) A crack growth analysis shall be performed in accordance with 3.3, which provides the requirements for crack growth mechanism, rate, analysis procedure and the stress intensity factor $K$ calculation procedure.
(e) If applicable, a flaw stability evaluation for upper shelf conditions shall be performed in accordance with 3.4.
(f) The flaw shall satisfy the acceptance criteria in Section 4.

3 ANALYTICAL EVALUATION

3.1 Flaw Characterization

(a) The flaw shall be evaluated at the detected (or postulated) location in the partial-penetration nozzle weld, unless otherwise determined by 3.1(d), and shall be characterized as an axial crack.
(b) If a flaw is postulated in the J-groove weld, the flaw geometry shall be treated as an axially-oriented planar crack. The azimuthal location of the postulated flaw around the partial-penetration weld shall be at the most limiting position with regard to stress. Several positions may be required to be evaluated to assure the worst location was assessed.
(c) Figure 5 provides an example of a limiting flaw geometry showing the orientation and shape of a postulated flaw, where the area of the flaw is assumed to cover the full width of the J-groove weld, including the axial areas of buttering.
(d) For multiple nozzle penetrations in a vessel head, the detected or postulated flaws in one or more locations may be assumed to occur at the outermost nozzle (steepest angle of penetration), as a conservative bounding analysis condition.

3.2 Loading Conditions

(a) The design basis loads under Service Levels A, B, C, and D shall be evaluated.
(b) Design transients shall be evaluated for steady-state and cyclic loading conditions resulting from operation and test conditions, to include pressure and nozzle loads (dead weight, seismic, etc.), and thermal stresses resulting from fluid temperature changes.
(c) Weld residual stresses shall be included in the determination of allowable flaw size and flaw growth during operation, as applicable.

3.3 Flaw Growth Analysis

(a) A flaw growth analysis shall be performed for normal operating, upset, and test conditions, including the design transients prescribed in the system Design Specification to determine the flaw size at the end of the evaluation period. Sustained loads from pressure, steady-state thermal expansion, applied mechanical loads during normal operating conditions, and residual stress from fabrication, shall be evaluated in the flaw growth analysis.
(b) Evaluation of crack growth mechanisms that can affect flaw propagation shall include fatigue crack growth for the ferritic base metal and cladding material, fatigue crack growth for the nozzle base material, and stress corrosion cracking (SCC) for any materials susceptible to cracking under steady-state loads, due to environmental effects.
(c) The procedures in Nonmandatory Appendix O, O-3000 may be used. Crack growth shall be calculated at multiple points along the crack front. The increment of the crack size and shape may be based on the maximum amount of crack growth along the crack front.

(d) The fatigue crack growth rate of the ferritic base metal shall be in accordance with Nonmandatory Appendix A, A-4300. The fatigue crack growth and SCC growth rates for austenitic base and weld material shall be in accordance with Nonmandatory Appendix C, C-8000. Other crack growth rate curves may be used in the analytical evaluation, if technically justified.

(e) If crack growth due to fatigue and SCC can occur simultaneously, crack growth from each mechanism shall be summed in the approximate chronological order of occurrence.

(f) The stress intensity factor, \( K \), shall be calculated by suitable analysis methods, such as those described in Nonmandatory Appendix K, K-4000 or Nonmandatory Appendix O, O-3000. When determining \( K \) or \( J \) using the finite element analysis (FEA) method, the procedures given in Nonmandatory Appendix A of this Case may be used to calculate these factors for the appropriate loading conditions described in 3.2.

3.4 Flaw Stability for Upper Shelf Conditions

(a) The evaluation for the allowable flaw size shall be performed for comparing with the end-of-evaluation period flaw size. The calculation of the stress intensity factor shall be performed in accordance with 3.3(f).

(b) If the final flaw penetration resides in the ferritic base material, or if the postulated flaw size is purposely defined to be larger than the weld and associated austenitic materials, the allowable flaw size shall be calculated using the fracture toughness of the ferritic base metal.

(c) Calculation of \( J \)-integral

(1) Applied \( J \)-Integral. Calculation of the \( J \)-integral due to applied loads shall account for elastic-plastic behavior of the stress-strain curve for the material. If linear elastic fracture mechanics with small scale yielding applies, the \( J \)-integral may be calculated using crack-tip stress intensity factor formulae with a plastic-zone correction. The plastic-zone correction shall be calculated prior to application of any structural factors on applied loads. Nonmandatory Appendix K, Article K-4000 provides a method for performing the calculation. The methodology and calculations shall be documented.

(2) Selection of the \( J \)-Integral Resistance Curve for Upper Shelf Conditions. The \( J \)-integral resistance versus crack-extension curve (\( J-R \) curve) shall be a conservative representation of the toughness of the controlling material at upper shelf temperatures in the operating range at the location of the flaw. One of the following shall be used to determine the \( J-R \) curve.

(-a) A \( J-R \) curve may be generated for the material by following accepted test procedures. The \( J-R \) curve shall be based on the proper combination of flaw orientation, temperature, and fluence level. Crack extension shall be ductile tearing with no cleavage.

(-b) A \( J-R \) curve may be generated from a \( J \)-integral database obtained from the same class of material with the same orientation, using correlations for effects of temperature, chemical composition, and fluence level. Crack extension shall be ductile tearing with no cleavage.

(-c) As an alternative to (-a) or (-b), an indirect method of estimating the \( J-R \) curve may be used in the analytical evaluation, provided the method is technically justified by the Owner for the material.

(d) Flaw stability evaluation

(1) The equilibrium requirement for stable flaw extension is

\[
J = J_R
\]

where,

\[
J = \text{the } J \text{-integral due to applied loads for the flaw}
\]

\[
J_R = \text{the } J \text{-integral resistance to ductile tearing for the material}
\]

(2) The requirement for flaw stability under ductile tearing is
\[ \frac{\partial J}{\partial a} < \frac{dj_R}{da}, \quad \text{at} \quad J = J_R \]  

(2)

where

\( \frac{\partial J}{\partial a} \) = partial derivative of the applied J–integral with respect to flaw depth, \( a \), with constant load

\( \frac{dj_R}{da} \) = slope of the J-R curve

Stable flaw extension shall be demonstrated with Eq. (2) for all Service Level loading conditions.

4 Acceptance Criteria

(a) Ductile to brittle transition temperature region - When a ferritic head, shell, or pipe material adjacent to the penetration nozzle is in the ductile to brittle transition temperature region, a flaw is acceptable if the applied stress intensity factor, \( K_p \), satisfies the acceptance criteria in IWB:3610.

(b) Upper shelf temperature range – A ferritic head, shell, or pipe material adjacent to the penetration nozzle is on the upper shelf of the Charpy energy curve when the metal temperature exceeds the upper shelf transition temperature, \( T_c \). \( T_c \) is defined as follows:

(U. S. Customary Units)  
\[ T_c = 0.82RT_{NDT} + 154.8^\circ \text{F} \]

(SI Units)  
\[ T_c = 0.82RT_{NDT} + 82.8^\circ \text{C} \]

The effect of radiation embrittlement shall be included in determining \( RT_{NDT} \).

(c) When the flaw is in the upper shelf temperature range, the acceptance criteria described below may be used.

(1) Acceptance criteria based solely on limited ductile crack extension

(-a) For Level A and B conditions, \( J \) shall be evaluated at loads equal to 2.0 times the primary loads and 1.0 times the secondary loads, including the thermal stresses. The applied \( J \) shall be less than or equal to the \( J \)-integral of the material at a ductile crack extension of 0.10 in. (2.5 mm).

(-b) For Level C and D conditions, \( J \) shall be evaluated at loads equal to 1.5 times the primary loads and 1.0 times the secondary loads, including the thermal stress. The applied \( J \) shall be less than or equal to the \( J \)-integral of the material at a ductile crack extension of 0.10 in. (2.5 mm).

(-c) The primary stress limits of NB-3000 shall be satisfied, assuming a local area reduction of the pressure retaining membrane equal to the area of the end-of-evaluation-period flaw, as determined using the flaw characterization rules of IWA-3000.

(2) Acceptance criteria based on limited ductile crack extension and stability

(-a) For Level A and B conditions, the following requirements shall be satisfied:

(-1) For ductile crack extension, \( J \) shall be evaluated at loads equal to 1.5 times the primary loads and 1.0 times the secondary loads, including thermal stresses. The applied \( J \) shall be less than or equal to the \( J \)-integral of the material at a ductile crack extension of 0.10 in. (2.5 mm).

(-2) The flaw shall be stable at loads equal to 2.14 times the primary loads and 1.0 times the secondary loads, including thermal stresses. Flaw stability shall be determined in accordance with 3.4.

(-3) The primary stress limits of NB-3000 shall be satisfied after stable ductile crack extension.

(-b) For Level C and D conditions, the following requirements shall be satisfied.

(-1) For ductile crack extension, \( J \) shall be evaluated at loads equal to 1.25 times the primary loads and 1.0 times the secondary loads, including thermal stresses. The applied \( J \) shall be less than or equal to the \( J \)-integral of the material at a ductile crack extension of 0.10 in. (2.5 mm).
(-2) The flaw shall be stable at loads equal to 1.2 times the primary loads and 1.0 times the secondary loads, including thermal stresses. Flaw stability shall be determined in accordance with 3.4.

(-3) For Level D conditions, the total end-of-evaluation-period flaw depth, including stable ductile crack extension, shall be less than or equal to 75% of the wall thickness, and the remaining ligament shall not be subject to tensile instability. For ligament tensile stability, the internal pressure shall be less than $P_i$, where $P_i$ is the internal pressure to cause tensile instability of the remaining ligament.

(d) If the acceptance criteria are not satisfied, corrective actions shall be performed by the Owner, such as reducing the evaluation period to achieve an acceptable operating period or performing a repair.
Figure 5. Examples of Postulated Flaw Orientation and Characterized Flaw Shape for Two Nozzle Penetration Configurations
Nonmandatory Appendix A

Stress Intensity Factor Calculation Methods
for Flaw Evaluation of Partial-Penetration Nozzle J-groove Welds

A-1 SCOPE

This nonmandatory appendix describes acceptable methods to calculate the stress intensity factor (SIF, $K$) for flaw evaluation of a penetration nozzle J-groove weld. The postulated flaw is an axial flaw at the J-groove weld joint and penetration nozzle as shown in Figure A-1 for example. The calculation procedures in this appendix include the method utilizing the $J$ calculation function of finite element analysis (FEA) codes (Section A-2).

![Finite Element Modeling Area and Constraint Conditions](image)

Figure A-1. Finite Element Modeling Area and Constraint Conditions
A-2 SIF CALCULATION BASED ON FINITE ELEMENT ANALYSIS

A-2.1 Finite Element Analysis Model and Constraint Conditions
The finite element analysis (FEA) model geometry and constraint conditions for a nozzle penetration shall account for the J-groove weld geometry, flaw geometry, and boundary conditions. Figure A-1 shows a simple example of a FEA model that represents a single nozzle configuration. For a single nozzle model, the equivalent stiffness of the vessel head shall be used, where the equivalent stiffness is determined considering multiple nozzles except for the adjacent nozzles. More sophisticated FEA models that include the geometry of multiple nozzles and penetration angles may be used.

A-2.2 Element Type
The element type shall be a three-dimensional solid element. The elements adjacent to the crack tip should enable calculation of the stress intensity factor, K, or J-integral, J. Some FE codes only allow the use of the brick element type for the closed area for the calculation of J. In this situation the tetragon and triangular prism shall be characterized by degeneration of the brick element. For these elements, the same shape function as the brick element shall be used. If degeneration is applied to the element at the crack tip, it may be necessary to use a quarter-point element whose middle node moves to the quarter position from the crack tip on the side. The accuracy of J of a higher order element type for this shape is not confirmed.

A-2.3 FEA Mesh Size
(a) Fine mesh division is required adjacent to the crack tip for calculation of the stress intensity factor, K, or J. At maximum of 0.079 in. (2 mm) of mesh size is recommended. Large aspect ratios and skewness angles of element shapes in the region of the crack shall be avoided. The meshes should be divided so the number of layers is greater than or equal to the number of paths at the crack front.
(b) At least six (6) crack-tip contour paths shall be evaluated to confirm the J-integral solution has converged for the given mesh size.

A-2.4 Loading Condition
The loads to be analyzed shall include pressure, thermal load, mechanical load, seismic load, and residual stress. The analysis result of residual stress for the outermost penetration nozzle may be used to conservatively bound the residual stress at a specific nozzle location.

A-2.6 Material Properties
Material properties of each component corresponding to the loading conditions shall be used. Those for mechanical loads, including pressure and seismic loads, shall be Young’s modulus and Poisson’s ratio. Those for heat conduction and thermal stress analyses shall be thermal conductivity, thermal diffusivity (or specific heat and density), thermal expansion coefficient, Young’s modulus and Poisson’s ratio. The zero stress temperature shall be confirmed.

A-2.7 Stress Intensity Factors
(a) Stress intensity factor K may be calculated from J by FEA. For calculation using the J-integral method, more than two contour paths with sequential numbers shall be used and the average of J integrals shall be taken. If the scatter of values for J-integral are not within 10%, it is recommended that recalculation using a finer mesh model is performed or K at a crack front with smaller scatter is interpolated to K at another crack front with larger scatter. In the case of the surface point, extrapolation is permitted. It is recommended that the obtained K be compared with that calculated from a similar-shaped flaw and similar load level.
(b) A positive value of the J-integral shall be obtained in the case of a compressive stress field.
Note to Editor: Applicability: 2007 Edition through 2021 Edition