APPENDIX A:

EVALUATION OF FLAWS IN PWR REACTOR VESSEL UPPER HEAD PENETRATION NOZZLES

SECTION 1.0
INTRODUCTION

1.1 SCOPE

(a) This Appendix provides a method for determining the acceptability for continued service of pressurized water reactor vessel upper head penetration nozzles. The evaluation methodology is based on the conclusion that head penetration nozzles are ductile materials, where the ability to reach limit load is assured. Flaws are evaluated by comparing the maximum flaw dimensions determined by flaw growth analysis with the maximum allowable flaw dimensions at the end of a selected evaluation period.

(b) This Appendix provides rules for flaw modeling and evaluation. Flaw growth analysis is based on growth due to fatigue, stress corrosion cracking (SCC), or both, as appropriate to the flaw under evaluation. The flaw acceptance criteria of Enclosure 1 provide a structural margin on failure for plastic limit load. The criteria may be used to determine the acceptability of flawed head penetration nozzles for continued service until the next inspection, or conversely, to determine the time interval until a subsequent inspection. In all cases, the requirements of IWB-2420(b) of Section XI shall be met.

1.2 PROCEDURE

The following is a summary of the analytical procedure.

(a) Determine the actual flaw configuration from the measured flaw in accordance with IWA-3000 of Section XI.

(b) Using Section 2.0, resolve the actual flaw into circumferential and axial flaw components.

(c) Determine the stresses at the location of the detected flaw for Service Levels A and B conditions including weld residual stresses.

(d) Using the analytical procedures described in Section 3.0, determine the flaw parameters a_f and ℓ_f.

(e) Using the flaw parameters a_f and ℓ_f, apply the flaw evaluation criteria of Enclosure 1 to determine the acceptability of the flawed nozzle for continued service.

SECTION 2.0
FLAW MODEL FOR ANALYSIS

2.1 SCOPE

This Section provides criteria for flaw shape, consideration of multiple flaws, flaw orientation, and flaw location, which are used in the comparison with the allowable flaw size.

2.2 FLAW SHAPE

The flaw shall be completely bounded by a rectangular or circumferential planar area in accordance with the methods described in IWA-3300 of Section XI. Fig's. 2.2-1 and 2.2-2 illustrate flaw characterization for circumferential and axial flaws.

2.3 PROXIMITY TO CLOSEST FLAW

For multiple neighboring flaws, if the shortest distance between the boundaries of two neighboring flaws is within the proximity limits specified in IWA-3300 of Section XI, the neighboring flaws shall be bounded by a single rectangular or circumferential planar area in accordance with IWA-3300.

2.4 FLAW ORIENTATION

Flaws that do not lie in either an axial[1] or a circumferential[2] plane shall be projected into these planes in accordance with the provisions of IWA-3340 of Section XI. The axial and circumferential flaws obtained by these projections shall be evaluated separately in accordance with Section 3.0.

2.5 FLAW LOCATION

For the purpose of analysis, the flaw shall be considered in its actual location. The applicable stress, including weld residual stress, shall be determined at this location. Surface or subsurface flaw characterizations shall be used, depending on the type of flaw. If the flaw is subsurface but within the proximity limit in Section XI of IWA-3340 of the surface of the component, the flaw shall be considered a surface flaw and bounded by a rectangular or circumferential planar area with the base on the surface.

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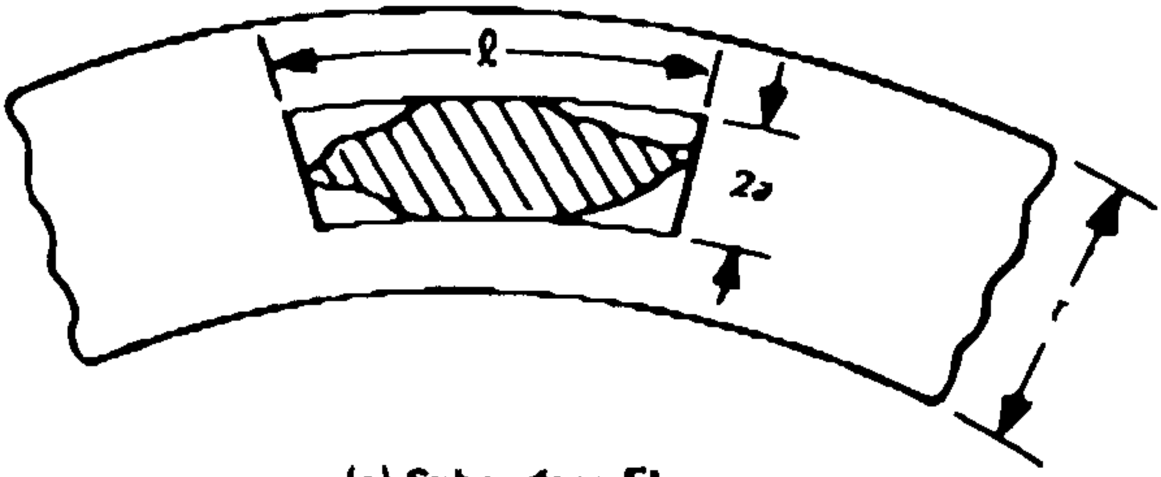
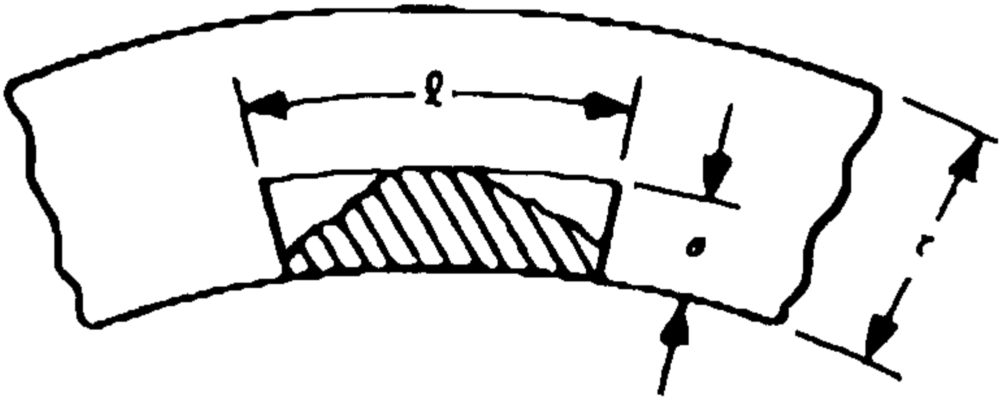
[1] A plane parallel to the nozzle axis.

[2] A plane parallel, within +/- 10°, of the plane of the attachment weld, as illustrated in Fig. I of Enclosure 1.

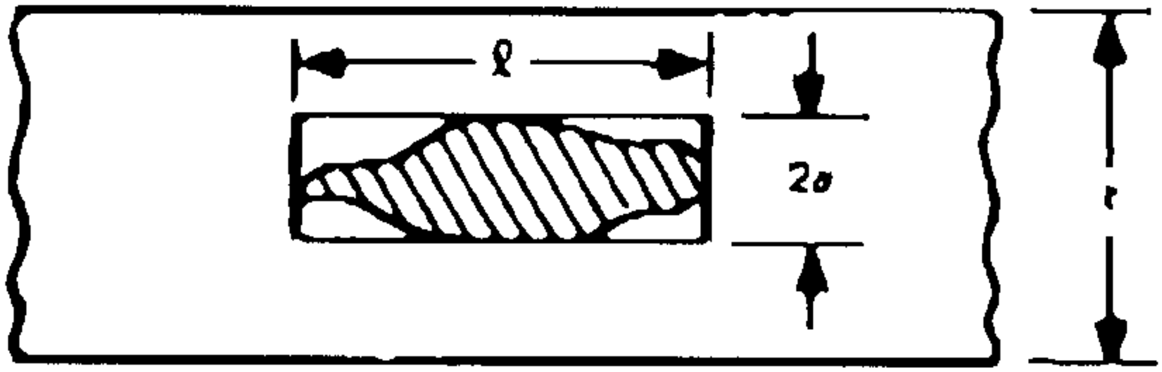


(a) Subsurface Flaw

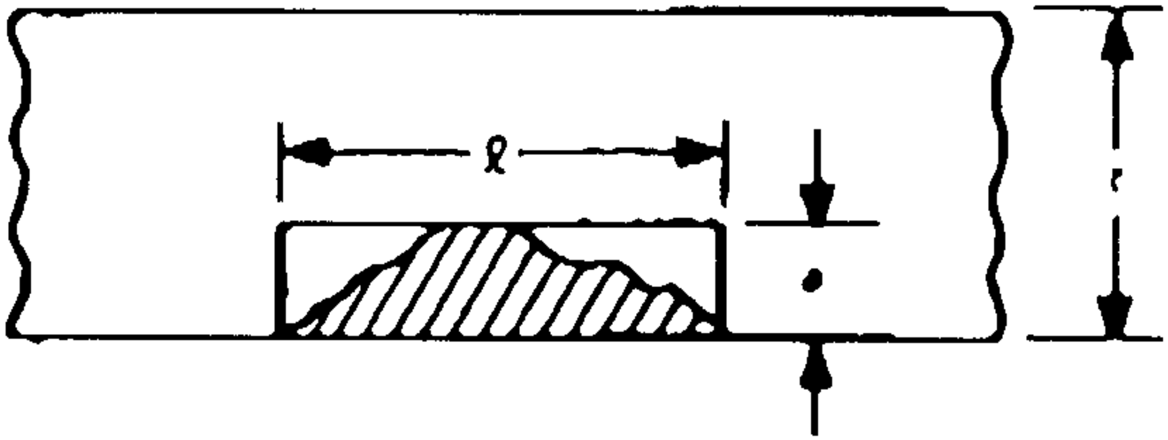


(b) Surface Flaw

Fig. 2.2-1 Flaw Characterization – Circumferential Flaws



(a) Subsurface Flaw



(b) Surface Flaw

Fig. 2.2-2 Flaw Characterization – Axial Flaws

SECTION 3.0
ANALYSIS

3.1 SCOPE

This Section provides the methodology for flaw evaluation and describes the procedures to determine the flaw size at the end of the evaluation period.

3.2 FLAW GROWTH ANALYSIS

(a) The maximum depth a_f and the maximum length ℓ_f to which the detected flaw will grow in the plane of the flaw by the end of the evaluation period shall be determined. This Section describes the procedures for the flaw growth analysis.

(b) Crack growth in Alloy 600 head penetration nozzles can be due to cyclic fatigue flaw growth, SCC under sustained load, or a combination of both. Flaw growth analysis shall be performed for normal operating conditions, as defined in A-5200 of Appendix A to Section XI. Flaw growth is governed by the applied stress intensity factor.

3.3 STRESS INTENSITY FACTOR DETERMINATION

Because the total stresses in this region are typically non-linear, it is recommended that the distribution be fit to a cubic polynomial, as shown below.

$$\sigma(x) = A_0 + A_1 x + A_2 x^2 + A_3 x^3 \quad (1)$$

where x = the coordinate distance into the nozzle wall
σ = stress perpendicular to the plane of the crack
A_j = coefficients of the cubic polynomial fit

For a surface flaw with a given ratio of length to depth, the stress intensity factor expression of Raju and Newman [1] may be used. The stress intensity factor K_I (Φ) can be calculated anywhere along the crack front. The following expression is used for calculating K_I (Φ).

The units of K_I (Φ) are $MPa\sqrt{m}$.

$$K_I = \left[\frac{\pi a}{Q}\right]^{0.5} \sum_{j=0}^{3} G_j \left(a/c,\, a/t,\, t/R,\, \Phi\right) A_j\, a^j \quad (2)$$

Where factors G_0, G_1, G_2, and G_3 are obtained from the procedure outlined where Φ is the angular location around the crack in reference [1]. "a" is the crack depth, and "c" is the half-crack length, while "t" is the wall thickness. "R" is the inside radius of the tube, and "Q" is the shape factor, as defined in reference [1].

Alternatively, procedures such as those described in A-3000 of Appendix A to Section XI may be used to calculate the stress intensity factor.

3.4 FLAW GROWTH DUE TO FATIGUE

(a) The fatigue crack growth rate of Alloy 600 material in PWR water environments can be characterized in terms of the range of the applied stress intensity factor, K_I. This characterization is of the form

$$\frac{da}{dN} = CS_R S_{ENV} \Delta K^n \qquad (3)$$

where n and C are constants dependent on the material and environmental conditions. These parameters are based on crack growth data obtained from specimens of the same material specification and product form, or suitable alternative. Material variability, environment, test frequency, mean stress, and other variables that affect the data shall be considered.

(b) The fatigue crack growth behavior of Alloy 600 materials is affected by temperature, R ratio (K_{min}/K_{max}), and environment. Reference fatigue crack growth rates for PWR water environments are given by Eq (3), where

$$C = 4.835\times10^{-14} + 1.622\times10^{-16}T - 1.490\times10^{-18}T^2 + 4.355\times10^{-21}T^3$$

$$S_R = \left[1 - 0.82R\right]^{-2.2}$$

$$S_{ENV} = 1 + A\left[CS_R\Delta K^n\right]^{m-1} T_R^{\,1-m}$$

$A = 4.4\times10^{-7}$

$m = 0.33$

$n = 4.1$

$T =$ *degrees C*

$\Delta K =$ *range of stress itensity factor* $MPa\sqrt{m}$

$R = K_{\min} / K_{\max}$

$T_R =$ rise time, set at 30 sec.

$da/dN =$ m/cycle

(c) To determine the maximum potential for fatigue flaw growth of the detected flaw during normal operating conditions, a cumulative fatigue flaw growth study of the nozzle shall be performed. The design transients prescribed in the system Design Specification that apply during the evaluation period shall be included. Each transient shall be considered in approximate chronological order as follows:

(1) Determine ΔK, the maximum range of K_I fluctuation associated with the transient.

(2) Find the incremental flaw growth corresponding to ΔK from the fatigue flaw growth rate data.

(3) Update the flaw size and proceed to the next transient.

(d) The above procedure, after all transients have been considered, yields the final flaw size, a_f and ℓ_f, at the end of the evaluation period, considering fatigue crack growth alone.

3.5 FLAW GROWTH DUE TO STRESS CORROSION CRACKING

(a) Flaw growth due to SCC is a function of the material condition, environment, the stress intensity factor due to sustained loading, and the total time that the flaw is exposed to the environment under sustained loading. The procedure for computing SCC flaw growth is based on experimental data relating the flaw growth rate (da/dt) to the sustained load stress intensity factor K_I. Sustained loads resulting from pressure and steady state thermal stresses, as well as weld residual stresses, shall be included. The procedure used for determining the cumulative flaw growth is as follows

(1) Determine the stress intensity factor K_I for a given steady state stress condition.

(2) Calculate the incremental growth of the flaw depth and length corresponding to the period for which the steady state stress is applied. This can be obtained from the relationship between da/dt and K_I. A

sufficiently small time interval shall be selected to ensure that the flaw size and the associated K_I value do not change significantly during this interval.

(3) Update the flaw size.

(4) Continue the flaw growth analysis for the period during which the stress exists until the end of the evaluation period.

(b) The above procedure yields the final flaw size, a_f and ℓ_f, at the end of the evaluation period, considering SCC flaw growth alone.

Fig. 3.5-1 presents the crack growth rate versus stress intensity factor plot given by Eq. 4, when K_I is greater than K_{th}.

$$\dot{a} = \exp\left[-\frac{Q_g}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)\right]\alpha\left(K_I - K_{th}\right)^{\beta} \quad (4)$$

where:

$\dot{a}$ = crack growth rate at temperature T in m/s

Q_g = thermal activation energy for crack growth

= 130 kJ/mole

R = universal gas constant

= $8.314\text{x}10^{-3}$ kJ/mole °K

T = absolute operating temperature at location of crack, °K

T_{ref} = absolute reference temperature used to normalize data

= 598.15 °K

α = crack growth rate coefficient

= $2.67\text{x}10^{-12}$ at 325°C for $\dot{a}$ in units of m/s and K_I in units of $\text{MPa}\sqrt{\text{m}}$

K_I = crack tip stress intensity factor, $\text{MPa}\sqrt{\text{m}}$

K_{th} = crack tip stress intensity factor threshold for SCC

= 9 $\text{MPa}\sqrt{\text{m}}$

β = exponent

= 1.16

When K_I is less than or equal to K_{th}, $\dot{a} = 0$.

For calculation of crack growth from the outside surface of the tube, in the annulus region between the tube and the head, a factor of two shall be applied to the crack growth rate above.

3.6 FLAW GROWTH DUE TO A COMBINATION OF FATIGUE AND SCC

When the service loading and the material and environmental conditions are such that the flaw is subjected to both fatigue and SCC growth, the final flaw size a_f and ℓ_f are obtained by adding the increments in flaw size due to fatigue and SCC computed in accordance with the procedures described above. The cyclic loads shall be considered in approximately chronological order.

3.7 FLAW EVALUATION

The allowable end-of-evaluation period flaw sizes are provided in Table I of Enclosure 1. The allowable flaw sizes specified in these tables are independent of the applied stress level.

4.0 REFERENCES

1. Newman, J. C. and Raju, I. S., “Stress Intensity Factor Influence Coefficients for Internal and External Surface Cracks in Cylindrical Vessels,” in Aspects of Fracture Mechanics in Pressure Vessels and Piping, PVP Vol. 58, ASME, 1982, pp. 37-48.

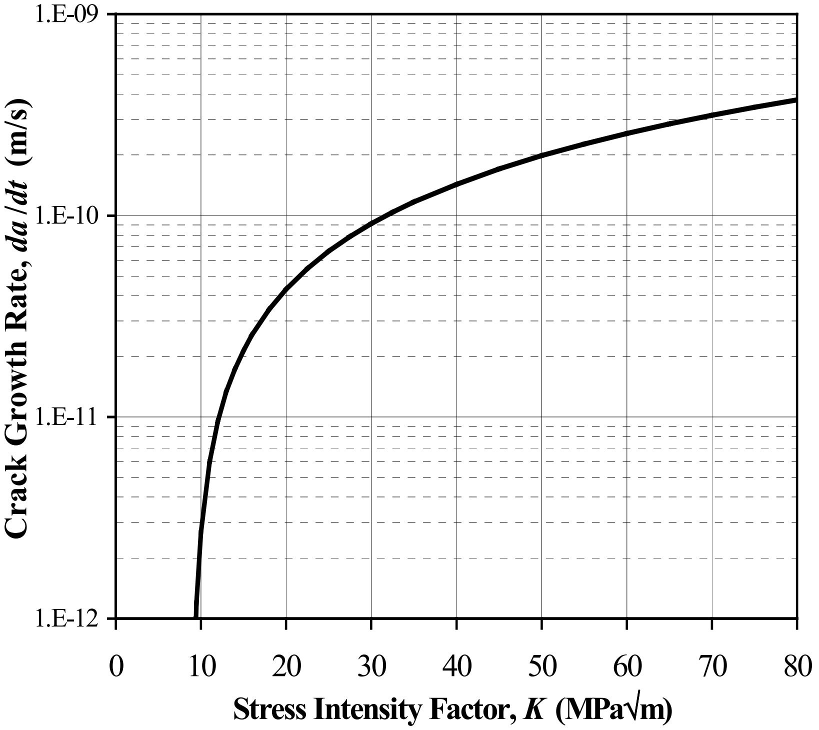


Fig. 3.5-1 **Recommended Curve for Prediction of SCC in Alloy 600 Reactor Vessel Upper Head Penetration Nozzles**