Appendix G Errata – rounding error for SI units

Alternatively, if a material-specific temperature value, T_0, determined in accordance with ASTM E1921, Standard Test Method for the Determination of Reference Temperature, T_0, for Ferritic Steels in the Transition Range, is available, a reference temperature, RT_{T0}, may be used in place of RT_{NDT}. The reference temperature RT_{T0} is defined as

(U.S. Customary Units)

$$RT_{T0} = T_0 + 35°F$$

(SI Units)

$$RT_{T0} = T_0 + 19.4^0C$$

Determination of RT_{T0} shall be the responsibility of the Owner and subject to the approval of the regulatory authority having jurisdiction at the plant site.

Editor – please keep the tracked value of 19.4 and do not round off to 19

Working Group Flaw Evaluation Errata

February 11, 2014

Nonmandatory Appendix K

1. p.451 K-4322 – "safety factor" should be "structural factor"
   (same in 2010 Code 2011a Addenda)

2. p.453 K4331(b) eqn 5 – missing parenthesis in SI units equation
   $$W=0.235[1+(1.6x10^{-6})(CR)t^2/((SF)P_5)]$$
   (same in 2010 Code 2011a Addenda)

3. p.453 K4331(b) - Units missing on left hand side of equation
   $$6\ in(152\ mm) \leq t \leq 12in(305mm)$$
   (same in 2010 Code 2011a Addenda)

4. p.453 K4331(b) – mm . units missing on left hand side of units equation;
   Add mm. units term to read 2.25 **(15.5)** $\leq$ (SF)Ps $\leq$ 9.00 ksi (62 MPa)

A-3000 ANALYSIS

A-3100 SCOPE

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

A-3200 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 Appendix describes the procedures for the flaw growth analysis.

(b) Crack growth in austenitic 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 Section XI, A-5200 of Appendix A. Flaw growth is governed by the applied stress intensity factor.

A-3210 Stress Intensity Factor Determination

(a) Because the total stresses in this region are typically non-linear, it is recommended that the distribution be fit to a polynomial, as shown in eq. (1).

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

where

x = the coordinate distance into the nozzle wall
σ = stress perpendicular to the plane of the crack that produces the minimum K_I along the crack front
A_i = coefficients of the polynomial fit

The following general expression is used to determine the stress intensity factor, K_I, along the crack front for a surface flaw with the m^{th} order polynomial stress distribution. This general expression uses the influence coefficients, Gj, and shape factor, Q, which may be determined using the procedure defined in Section XI, A-3000. Alternative procedures may be used to determine the influence coefficients and shape factor. The technical basis for the influence coefficients and shape factor used to calculate the stress intensity factor shall be documented.

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

where

G_j = influence coefficients
a = crack depth
c = half-crack length
m = polynomial order for defined stress distribution
t = wall thickness
R = inside radius of the nozzle
Q = shape factor

(b) Other methods may be used to calculate the stress intensity factor[3] when technically justified and documented.

A-3220 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:

$$da/dN = C_o\,(\Delta K)^n \quad (3)$$

where n and C_o 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 in Section XI, C-8411

(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 asociated 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.

A-3230 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

[3] *Examination of Service Cracks in CRDM Nozzles and Relevance to Flaw Evaluation Procedures*, G. Wilkowski, D. Rudland, and H. Xu, ASME Conf. Proc. 2006, PVP Vol. 6, pp. 453-459, DOI:10.1115/PVP2006-ICPVT-11-93995.

A-3200 FLAW GROWTH ANALYSIS

(a)

(*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 Appendix describes the procedures for the flaw growth analysis.

(*b*) Crack growth in austenitic 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 Section XI, A-5200 of Appendix A. Flaw growth is governed by the applied stress intensity factor.

A-3210 Stress Intensity Factor Determination Because the total stresses in this region are typically nonlinear, it is recommended that the distribution be fit to a ~~cubic~~ polynomial, as shown in eq. (1).

$\sigma(x) = A_0 + A_1x + A_2x^2 + A_3x^3 + \ldots + A_q x^m$

m

~~$\sigma(x) = A_0 + A_1x + A_2x^2 + A_3x^3$~~ (1)

where

x = the coordinate distance into the nozzle wall

σ = stress perpendicular to the plane of the crack

that produces the maximum K_I along the crack ~~tip~~ front

A_i = coefficients of the ~~cubic~~ polynomial fit

The following general expression is used to determine the stress intensity factor, K_I, along the crack front for a surface flaw with the m^{th} order polynomial stress distribution. This general expression uses the influence coefficients, G_j, and shape factor, Q, which may be determined using the procedure defined in Section XI, A-3000. Alternative procedures may be used to determine the influence coefficients and shape factor. The technical basis for the influence coefficients and shape factor used to calculate the stress intensity factor shall be documented.

~~For a surface flaw with a given ratio of length to depth, the stress intensity factor expression of Raju and Newman[3] 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 $\sqrt{m}$.~~

m

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

where

G_j = influence coefficients

~~G_0, G_1, G_2, G_3 = factors obtained from the procedure outlined~~

~~Φ = angular location around the crack[3]~~

~~[3] 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.~~

a = crack depth
c = half-crack length
t = wall thickness
R = inside radius of the ~~tube~~ nozzle
Q = shape factor ~~as defined in footnote 3~~

m = polynomial order for defined stress distribution

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

(b) Other methods may be used to calculate the stress intensity factor[3] when technically justified and documented.

A-3220 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:

~~$da/dN = CS_R S_{ENV} \Delta K^n$~~ $da/dN = C_o(\Delta K)^n$ (3)

where n and ~~C~~ C_o ~~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).~~ in Section XI, ~~Appendix C,~~ C-8411.

~~$$C = 4.835 \times 10^{-14} + 1.622 \times 10^{-16} T - 1.490 \times 10^{-18} T^2 + 4.355 \times 10^{-21} T^3$$~~

~~$$ES_R = [1 - 0.82R]^{-2.2}$$~~

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

~~where~~

~~A = 4.4×10^{-7}~~
~~m = 0.33~~
~~n = 4.1~~
~~T = degrees C~~
~~ΔK = range of stress intensity 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 asociated with the transient.

[3] *Examination of Service Cracks in CRDM Nozzles and Relevance to Flaw Evaluation Procedures* G. Wilkowski, D. Rudland, and H. Xu, ASME Conf. Proc. 2006, PVP Vol. 6, pp. 453-459, DOI:10.1115/PVP2006-ICPVT-11-93995