The following select pages are an editorial markup of Item 10-783 (rewrite of Article 3000 of Appendix A). The editorial change is needed to make the definitions of M and N of the weight functions consistent with the open literature where Q does not have a plastic zone correction. In Article 3000, Q has always had the plastic zone correction. By replacing Q with Φ, the weight functions will have the correct form.

Pages 1 and 9 are for information. Pages 15 and 16 have the corrections.

ARTICLE A-3000
METHOD OF K_I DETERMINATION

A-3100 SCOPE

(a) This Article provides methods of calculating crack tip stress intensity factors, K_I, for subsurface and surface flaws using the representative stresses at the flaw location and acting normal to the plane of the flaw (Mode I). The solutions for K_I are based on either flat plate or cylindrical geometries, and can be used for subsurface flaws, and internal and external surface flaws in various types of components (e.g., vessels, pumps, valves, etc.), for which the flaw can be defined in terms of crack depth, a, for surface flaws (half crack depth for subsurface flaws), wall thickness, t, and component curvature, R_i/t (ratio of inside radius to wall thickness).

(b) The flaw shall be represented by an ellipse or semi-ellipse, as applicable, as shown in Figure A-3100-1. K_I for the appropriate flaw model shall be determined using the stress representation described in A-3200, and the equations provided in A-3300 for subsurface flaws or A-3400 for surface flaws.

A-3200 STRESSES

(a) When defining the stresses acting at the flaw location, applied stresses from all forms of loading, including internal pressure, thermal transients, cladding-induced stresses, and weld residual shall be evaluated. When surface flaws are in contact with the pressure-side of the component, the pressure acting on the crack faces shall be included in the determination of K_I.

(b) When stress distributions are determined using a numerical stress analysis method, stress values are obtained at discrete locations. Stress distribution may be represented by a polynomial equation as described in A-3210. Stress distribution may also be represented over discrete intervals as described in A-3220.

A-3210 POLYNOMIAL STRESS REPRESENTATION

The stress distribution may be represented by a polynomial. The selection of the order of the polynomial fit is established based on achieving the best fit to the actual stress variation. For nonlinear stress variations through the wall of the component, higher order regression fits up to 4th order might be required. Two acceptable fitting methods, as described in A-3211 and A-3212, may be used; namely, stress fit over the crack depth, or stress fit over the wall thickness of the component.

where

$$C_0 = A_0 - A_1\left(\frac{d}{a}\right) + A_2\left(\frac{d}{a}\right)^2 - A_3\left(\frac{d}{a}\right)^3 + A_4\left(\frac{d}{a}\right)^4$$

$$C_1 = \left(\frac{t}{a}\right)\left[A_1 - 2A_2\left(\frac{d}{a}\right) + 3A_3\left(\frac{d}{a}\right)^2 - 4A_4\left(\frac{d}{a}\right)^3\right]$$

$$C_2 = \left(\frac{t}{a}\right)^2\left[A_2 - 3A_3\left(\frac{d}{a}\right) + 6A_4\left(\frac{d}{a}\right)^2\right]$$

$$C_3 = \left(\frac{t}{a}\right)^3\left[A_3 - 4A_4\left(\frac{d}{a}\right)\right]$$

$$C_4 = A_4\left(\frac{t}{a}\right)^4$$

d = distance from the intersection of the major and minor axes of the flaw to the nearest free boundary surface as shown in Figure A-3210-2

$A_0, A_1, A_2, A_3,$
A_4 = coefficients from eq. (1) that represent the stress distribution over the flaw depth, $-1 \le x/a \le 1$. When calculating K_I as a function of flaw depth, a new set of coefficients A_0 through A_4 shall be determined for each new value of flaw depth.

$G_0, G_1, G_2, G_3,$
G_4 = K_I coefficients provided in tabular format in A-3312 or in equational format in A-3313

The flaw shape parameter Q is calculated using the following equation:

$$Q = \Phi - q_y \tag{5}$$

For Information:
These definitions of Q and Φ have been used previously in Article 3000. For weight functions, Q has the definition of Φ in the open literature.

where

$$\Phi = 1 + 4.593\left(a/\ell\right)^{1.65}$$

ℓ = the length of the major axis of the flaw
a/ℓ = the flaw aspect ratio $0 \le a/\ell \le 0.5$
q_y = the plastic zone correction factor calculated using the following equation:

$$q_y = [(C_0G_0 + C_1G_1 + C_2G_2 + C_3G_3 + C_4G_4)/\sigma_{ys}]^2/6$$

σ_{ys} = material yield strength

(c) For stresses represented by eq. (2) where the stress is defined over the component thickness, the stress intensity factor is given by

$$K_I = (B_0G_0 + B_1G_1 + B_2G_2 + B_3G_3 + B_4G_4)\sqrt{\pi a/Q} \tag{6}$$

In eq. (10) and eq. (11), k_i and b_i are defined in eq. (3).

(b) For the surface point (Point 2) of a semi-elliptical surface crack as shown in Figure A-3100-1(b), the weight function is given by

$$m(x,a) = \frac{2}{(\pi x)^{1/2}}\left[1 + N_1\left(\frac{x}{a}\right)^{1/2} + N_2\left(\frac{x}{a}\right) + N_3\left(\frac{x}{a}\right)^{3/2}\right]$$

where weight function coefficients N_j are dependent on geometry of the structure and crack dimensions. The stress intensity factor calculated using the weight function method of eq. (9) and the piecewise linear stress of eq. (3) is given by

$$K_I = K_{IN0} + K_{IN1} N_1 + K_{IN2} N_2 + K_{IN3} N_3 \qquad (11)$$

where

$$K_{IN0} = \frac{4}{3\sqrt{\pi}} \sum_{i=1}^{n} \left[\sqrt{x_{i+1}}(k_i x_{i+1} + 3b_i) - \sqrt{x_i}(k_i x_i + 3b_i)\right]$$

$$K_{IN1} = \frac{1}{\sqrt{\pi a}} \sum_{i=1}^{n} \left[x_{i+1}(k_i x_{i+1} + 2b_i) - x_i(k_i x_i + 2b_i)\right]$$

$$K_{IN2} = \frac{4}{15a\sqrt{\pi}} \sum_{i=1}^{n} \left[x_{i+1}^{3/2}(3k_i x_{i+1} + 5b_i) - x_i^{3/2}(3k_i x_i + 5b_i)\right]$$

$$K_{IN3} = \frac{1}{3a\sqrt{\pi a}} \sum_{i=1}^{n} \left[x_{i+1}^{2}(2k_i x_{i+1} + 3b_i) - x_i^{2}(2k_i x_i + 3b_i)\right]$$

In eq. (10) and eq. (11), k_i and b_i are defined in eq. (3).

A-3422 Equations For Weight Function Coefficients M_j and N_j

(a) Coefficients M_j for j = 1, 2, and 3, to calculate K_I in A-3421(a), where G_i is evaluated at the deepest point (Point 1), are given by

$$M_1 = \frac{2\pi}{\sqrt{2\cancel{Q}}}(3G_1 - G_0) - \frac{24}{5} \quad \Phi$$

$$M_2 = 3$$

$$M_3 = \frac{6\pi}{\sqrt{2\cancel{Q}}}(G_0 - 2G_1) + \frac{8}{5} \quad \Phi$$

Solutions for G_0 and G_1 are provided in A-3412 and A-3413 for various flaw geometries.

(b) Coefficients N_j, for j = 1, 2, and 3, to calculate K_I in A-3421(b), where G_i are evaluated at the surface point (Point 2), is given by

$$N_1 = \frac{3\pi}{\sqrt{\cancel{Q}}\,{}_{\phi}}(2G_0 - 5G_1) - 8$$

$$N_2 = \frac{15\pi}{\sqrt{\cancel{Q}}\,{}_{\phi}}(3G_1 - G_0) + 15$$

$$N_3 = \frac{3\pi}{\sqrt{\cancel{Q}}\,{}_{\phi}}(3G_0 - 10G_1) - 8$$

Solutions for G_0 and G_1 are provided in A-3412 and A-3413 for various flaw geometries.

A-3500 FLAW MODEL SOLUTIONS

A-3510 SUBSURFACE FLAWS

In course of preparation. The tabular G_i coefficients for subsurface flaws in Tables A-3610-1 through A-3610-6 may be used. Interpolation within the listed values is permitted.

A-3520 SURFACE FLAWS IN FLAT PLATE

For surface flaws in a flat plate of finite thickness, the following expressions define the solution functions for determining the G_i coefficients in A-3413. For the deepest point (Point 1),

$$Y_0 = f_0$$
$$Y_1 = f_0 - f_1$$

where

$$f_0 = a_0 + a_1(a/t)^2 + a_2(a/t)^4$$

$$a_0 = 1.10190 - 0.019863(a/c) - 0.043588(a/c)^2$$
$$a_1 = 4.32489 - 14.9372(a/c) + 19.4389(a/c)^2 - 8.52318(a/c)^3$$
$$a_2 = -3.03329 + 9.96083(a/c) - 12.582(a/c)^2 + 5.3462(a/c)^3$$

and

$$f_1 = b_0 + b_1(a/t)^2 + b_2(a/t)^4$$

$$b_0 = 0.456128 - 0.114206(a/c) - 0.046523(a/c)^2$$
$$b_1 = 3.022 - 10.8679(a/c) + 14.94(a/c)^2 - 6.8537(a/c)^3$$
$$b_2 = -2.28655 + 7.88771(a/c) - 11.0675(a/c)^2 + 5.16354(a/c)^3$$

over the ranges $0 < a/t \leq 0.8$ and $0.2 \leq a/c \leq 1.0$, where $c = \ell/2$.

For the surface point (Point 2),

NONMANDATORY APPENDIX E
EVALUATION OF UNANTICIPATED OPERATING EVENTS

ARTICLE E-1000
INTRODUCTION

(13) E-1100 SCOPE

This Nonmandatory Appendix provides acceptance criteria and guidance for performing an engineering evaluation of the effects of an out-of-limit condition on the structural integrity of the reactor vessel beltline region. Showing compliance with the criteria in either E-1200 or E-1300 assures that the beltline region has adequate structural integrity for the unit to return to service. Evaluations performed using this Nonmandatory Appendix shall meet all the requirements of the Appendix.

(13) E-1200 ACCEPTANCE CRITERIA[52,53]

Adequate structural integrity of the reactor vessel beltline region is assured if the following applicable criterion is satisfied throughout the event:

(a) For isothermal pressure transients [i.e., $\Delta T_c/\Delta t < 10$°F/hr (5.5°C/hr)], the maximum pressure does not exceed the allowable values of Table E-1 at any value of $T_c - RT_{NDT}$.

(b) For pressurized thermal transients [i.e., $\Delta T_c/\Delta t \geq 10$°F/hr (5.5°C/hr)], the maximum pressure does not exceed the design pressure and $T_c - RT_{NDT}$ is not less than 55°F (31°C).

If compliance with the above applicable criterion is not shown, adequate structural integrity can be assured by satisfying the guidelines and criteria specified in E-1300.

E-1300 EVALUATION BY ANALYSIS

(a) Adequate structural integrity of the reactor vessel beltline region is assured if it can be shown by analysis using the input of Table E-2 that the following criterion is met throughout the event:

$$1.4\left(K_{Im} + K_{It}\right) + K_{Ir} \leq K_{Ic}$$

where

K_{Im} = stress intensity factor due to membrane stress
K_{It} = stress intensity factor due to thermal stress
K_{Ir} = stress intensity factor due to residual stress
K_{Ic} = fracture toughness per Article A-9000 IWA-9000

(b) If compliance with the above criterion cannot be shown, additional analyses or other actions shall be taken to ensure that acceptable margins of safety will be maintained during subsequent operation.

Table E-1
Maximum Allowable Pressure as a Function of $T_c - RT_{NDT}$ for Isothermal Pressure Transients [$\Delta T_c/\Delta t < 10$°F/hr (5.5°C/hr)] For design pressures greater than 2,400 psig (16.5 MPa)

$T_c - RT_{NDT}$ °F (°C)	Maximum Allowable Pressure, psig (MPa)
+ 25 (14) and greater	1.1 × Design
+ 15 (8)	2400 (16.5)
+ 10 (5.5)	2250 (15.5)
0 (0)	2000 (13.8)
−10 (−5.5)	1750 (12.1)
−25 (−14)	1500 (10.3)
−50 (−28)	1200 (8.3)
−75 (−42)	1000 (6.9)
−105 (−58)	850 (5.9)
−130 (−72)	800 (5.5)
−200 (−111)	750 (5.2)

GENERAL NOTE: Linear interpolation is permitted.

(13)

Table E-2
Evaluation Input for Plant and Event Specific Linear Elastic Fracture Mechanics Analysis

Variable	Value
Pressure	Event pressure time history
Temperature	Event temperature time history
Heat transfer	Event/plant specific flow/mixing conditions
Crack type	Semi-elliptical surface flaw
Minimum initiation crack size	$0.0 < a \leq 1.0$ in. (25 mm) [Note (1)]
Crack orientation	Longitudinal
K_{Ic}/K_I location	Surface and maximum depth
Clad effects	Clad to be considered in the thermal, stress, and fracture mechanics analyses [Note (2)]
Transition toughness	K_{Ic} per Article A-9000 IWA-9000
Upper shelf toughness	(In course of preparation)
Fluence	Fluence at the time of the transient
Shift curve	Regulatory Guide 1.99 Rev. 2
Residual stress	Appropriate distribution for the fabrication process, or linear distribution with +10 ksi (+69 MPa) at the inside surface and −10 ksi (−69 MPa) at the outside surface

NOTES:

(1) a = the maximum crack depth in the base metal

(2) The stresses due to the difference between the base metal and cladding thermal expansion coefficients need not be considered in the isothermal pressure transient evaluation [i.e., $\Delta T_c/\Delta t < 10°F/hr$ (5.5°C/h)].