NONMANDATORY APPENDIX A
ANALYSIS OF FLAWS

ARTICLE A-1000
INTRODUCTION

A-1100 SCOPE

This Appendix provides a procedure for determining the acceptability of flaws that have been detected during in-service inspection (excluding preservice inspection) that exceed the allowable flaw indication standards of IWB-3500. The procedure is based upon the principles of linear elastic fracture mechanics. This procedure applies to ferritic materials 4 in. (100 mm) and greater in thickness with specified minimum yield strengths of 50.0 ksi (350 MPa) or less in components having simple geometries and stress distributions. The basic concepts of the procedure may be extended to other ferritic materials (including clad ferritic materials) and more complex geometries; however, they are not intended to apply to austenitic or high nickel alloys. For purposes of analysis, indications that exceed the standards of IWB-3500 are considered flaws. The following is a summary of the analytical procedure.

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

(b) Characterize the flaw in accordance with IWB-3610.

(c) Using A-2000, resolve the actual flaw into a simple shape that can be analyzed.

(d) Determine the stresses at the location of the observed flaw for normal (including upset), emergency, and faulted conditions.

(e) Calculate stress intensity factors for each condition using the methods outlined in A-3000.

(f) Using the methods outlined in A-4000, determine the necessary material properties, including the effects of irradiation if applicable.

(g) Using the analytical procedures described in A-5000, determine the following critical flaw parameters:

\[
\begin{align*}
    a_f &= \text{expected end-of-life flaw size} \\
    a_c &= \text{minimum critical flaw size for normal conditions} \\
    a_i &= \text{minimum critical initiation flaw size for emergency and faulted conditions}
\end{align*}
\]

(h) Using the critical flaw parameters \(a_f\), \(a_c\), and \(a_i\), apply the flaw evaluation criteria of IWB-3600 to determine whether the observed flaw is acceptable for continued service.
ARTICLE A-3000
METHOD FOR KI DETERMINATION

A-3100 SCOPE

This Article provides a method for calculating stress intensity factors, KI, using the representative stresses at the flaw location determined by stress analysis. The solutions for KI are based on flat plate geometry and can be used for subsurface flaws and internal and external surface flaws in cylinders for all values of R/t (the ratio of mean radius to thickness).

A-3200 STRESSES

(a) For a surface or a subsurface flaw, the stresses at the flaw location shall be resolved into membrane and bending stresses. Residual stresses and applied stresses from all forms of loading, including pressure stresses and cladding-induced stresses, shall be considered. For non-linear stress variations through the wall, the actual stress distribution may be approximated by a linear distribution that accurately represents or bounds the stress field over the flaw depth. An example of linearization of a concave upward stress field is illustrated in Fig. A-3200-1. The linearized stress distribution may then be characterized by the membrane stress, σm, and the bending stress, σb, as shown in Fig. A-3200-1.

(b) For a surface flaw, the stresses normal to the plane of the flaw at the flaw location may be represented by a polynomial fit over the flaw depth by the following relationship:

\[
\sigma = A_0 + A_1 \left( \frac{x}{a} \right) + A_2 \left( \frac{x}{a} \right)^2 + A_3 \left( \frac{x}{a} \right)^3
\]

where:
- x = distance through the wall measured from the flawed surface
- a = crack depth
- \( A_0, A_1, A_2, A_3 \) = constants

Coefficients A0 through A3 shall provide an accurate representation of stress over the flaw plane for all values of flaw depths, 0 ≤ x/a ≤ 1, covered by the analysis. Stresses from all sources identified in (a) shall be considered. Alternatively, the actual stress distribution may be approximated by a linear distribution that accurately represents or bounds the stress field over the flaw depth. An example of linearization of a concave upward stress field is illustrated in Fig. A-3200-1(b).

A-3300 STRESS INTENSITY FACTOR EQUATIONS

The detected flaw shall be represented by an ellipse or a semiellipse as illustrated in Fig. A-3300-1. The stress intensity factors for the flaw model shall be determined using the stresses and flaw geometry described in A-3310 for subsurface flaws or A-3320 for surface flaws.

A-3310 SUBSURFACE FLAW EQUATIONS

Stress intensity factors for subsurface flaws shall be calculated using the membrane and bending stresses at the flaw location by the following equation:

\[
K_I = \left[ \sigma_m M_m + \sigma_b M_b \right] \frac{\pi a}{Q}
\]

where
- \( \sigma_m, \sigma_b \) = membrane and bending stresses, in accordance with A-3200(a)
- a = one-half the axis of elliptical flaw
- \( M_m \) = correction factor for membrane stress from Fig. A-3310-1
- \( M_b \) = correction factor for bending stress from Fig. A-3310-2

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

\[
Q = 1 + 4.593 \left( \frac{a}{\ell} \right)^{1.65} - q_y
\]

where
- \( \ell \) = the major axis of the flaw
- \( a/\ell \) = the flaw aspect ratio 0 ≤ a/\ell ≤ 0.5
- q_y = the plastic zone correction factor calculated using the following equation:

\[
q_y = \left[ \left( \sigma_m M_m + \sigma_b M_b \right) / \sigma_{yy} \right]^2 / 6
\]

where
- \( \sigma_{yy} \) = the material yield strength.

A-3320 SURFACE FLAW EQUATIONS

The stress intensity factor for a surface flaw may be determined from (a) or (b).
(a) Stress intensity factors for surface flaws should be calculated using the cubic polynomial stress relation by the following equation.

\[
K_I = \left[ \left( A_0 + A_p \right) G_0 + A_1 G_1 + A_2 G_2 + A_3 G_3 \right] \sqrt{\frac{\pi a}{Q}}
\]  

(5)

where

- \( a \) = flaw depth
- \( A_0, A_p, A_1, A_2, A_3 \) = coefficients from eq. A-3200(b)(1) that represent the stress distribution over the flaw depth, \( 0 \leq x/a \leq 1 \). When calculating \( K_I \) as a function of flaw depth, a new set of coefficients \( A_0, A_2 \) shall be determined for each new value of flaw depth.

- \( A_p \) = the internal vessel pressure, \( p \), for internal surface flaws. \( A_p = 0 \) for other flaws.

\( G_0, G_1, G_2, G_3 \) = free surface correction factors from Tables A-3220-1 and A-3220-2

\( Q \) = flaw shape parameter using eq. A-3310(3)

In the calculation of \( Q \) using eq. A-3310(3), \( q_p \) is calculated using eq. (6):

\[
q_p = \left[ \left( A_0 G_0 + A_p G_0 + A_1 G_1 + A_2 G_2 + A_3 G_3 \right) / \sigma_{ys} \right]^2
\]

(6)

(b) When the linearization method is used to convert the actual stress field into \( \sigma_m \) and \( \sigma_b \) stresses as illustrated in Fig. A-3200-1(b), eq. (7) shall be used to calculate \( K_I \):

\[
K_I = \left[ \left( \sigma_m + A_p M_m + \sigma_b M_b \right) \right] \sqrt{\frac{\pi a}{Q}}
\]

(7)
\[
\Delta K_{ch} = 5.5(1 - 0.8R) \text{ for } 0 \leq R < 1.0
\]

Reference fatigue crack growth rates for carbon and low alloy ferritic steels for air and water environments at \( \Delta K \geq \Delta K_{th} \) are given below.

(1) Reference fatigue crack growth behavior of the material exposed to air environments (subsurface flaws) is given by eq. (a)(1) with \( n = 3.07 \) and

\[
C_0 = 1.99 \times 10^{-10} S
\]  \( \text{(U.S. Customary Units)} \)  \( (2) \)

\[
C_0 = 3.78 \times 10^{-9} S
\]  \( \text{(SI Units)} \)  \( (2) \)

\( S \) is a scaling parameter to account for the \( R \) ratio and is given by \( S = 25.72 (2.88 - R)^{-3.07} \), where \( 0 \leq R \leq 1 \) and \( \Delta K_f = K_{\text{max}} - K_{\text{min}} \). For \( R < 0 \), \( \Delta K_f \) depends on the crack depth, \( a \), and the flow stress, \( \sigma_f \). The flow stress is defined by \( \sigma_f = \frac{1}{2}(\sigma_{ys} + \sigma_{ult}) \), where \( \sigma_{ys} \) is the yield strength and \( \sigma_{ult} \) is the ultimate tensile strength in units ksi (MPa) and \( a \) is in units in. (m). For \( -2 \leq R \leq 0 \) and

\[
K_{\text{max}} - K_{\text{min}} \leq 1.12 \sigma_f \sqrt{a}, S = 1 \text{ and } \Delta K_f = K_{\text{max}}. \text{ For } R < -2 \text{ and } K_{\text{max}} - K_{\text{min}} \leq 1.12 \sigma_f \sqrt{a}, S = 1 \text{ and } \Delta K_f = (1 - R) K_{\text{max}}/3. \text{ For } R < 0 \text{ and } K_{\text{max}} - K_{\text{min}} > 1.12 \sigma_f \sqrt{a}, S = 1 \text{ and } \Delta K_f = K_{\text{max}} - K_{\text{min}}. \]

The scaling constant \( C_0 \) from eq. (2) produces fatigue crack growth rates in units of in./cycle (mm/cycle) where \( \Delta K_f \) is in units of ksi\( \sqrt{\text{in.}} \) (MPa\( \sqrt{\text{m}} \)) and is intended for use when data from the actual product form are not available. Reference fatigue crack growth rate curves given by eqs. (a)(1) and (2) are provided in Fig. A-4300-1 (Fig. A-4300-1M).

(2) Reference fatigue crack growth behavior of material exposed to light-water reactor environments is given by eq. (a)(1) using \( \Delta K_f = K_{\text{max}} - K_{\text{min}} \). If \( K_{\text{min}} \) is equal to or less than zero, use \( R = 0 \). \( C_0 \) and \( n \) are given by whichever of the following results in the higher fatigue crack growth rate, \( da/dN \): (1) \( n \) and \( C_0 \) in (1) for air environments, or (2) either of the following, as applicable.

\[
\begin{align*}
& (a) \quad \text{For low } \Delta K_f \text{ values, }^{46} \quad n = 5.95 \text{ and } \quad C_0 = 1.02 \times 10^{-12} S \\
& (U.S. Customary Units)
\end{align*}
\]
Figure A-4200-1M
Lower Bound \( K_{\ell a} \) and \( K_{\ell c} \) Test Data for SA-533 Grade B Class 1, SA-508 Class 2, and SA-508 Class 3 Steels

The applicable set of material parameters \( n \) and \( C_o \) is determined by calculating the \( \Delta K_f \) at which the two curves intersect. This is given by

(U.S. Customary Units)

\[
\Delta K_f = 17.74 \text{ for } 0 \leq R \leq 0.25
\]

\[
\Delta K_f = \frac{17.74[(3.75 R + 0.06)/\sqrt{(26.9 R - 5.725)}]^{0.25}}{\text{for } 0.25 < R < 0.65}
\]

\[
\Delta K_f = 12.04 \text{ for } 0.65 \leq R \leq 1.0
\]

(SI Units)

\[
\Delta K_f = 19.49 \text{ for } 0 \leq R \leq 0.25
\]

\[
\Delta K_f = 2.13 \times 10^{-6} S
\]

where \( S \) is given by

\[
S = 1.0 \text{ for } 0 \leq R \leq 0.25
\]

\[
= 3.75 R + 0.06 \text{ for } 0.25 < R < 0.65
\]

\[
= 2.5 \text{ for } 0.65 \leq R \leq 1.0
\]
C-1200 PROCEDURE OVERVIEW

The following is a summary of the analytical procedure.

(a) Determine the configuration of the flaw in accordance with IWA-3000 using C-2000.

(b) Resolve the flaw into circumferential and axial flaw components using C-2000.

(c) Determine the stresses normal to the flaw at the location of the detected flaw for Service Levels A, B (including test conditions), C, and D using C-2500.

(d) Perform a flaw growth analysis in accordance with C-3000 to establish the end-of-evaluation-period flaw dimensions $a_f$ and $\ell_f$.

(e) Obtain pipe material properties at the temperature required for analysis, $\sigma_m$ and $F_{m}$. When material properties are not available, the properties in Tables C-8321-1 and C-8322-1 may be used.

(f) Using the screening procedure described in C-4000, determine the failure mechanism for the material and temperature for the end-of-evaluation-period flaw dimensions, $a_f$ and $\ell_f$.

(g) Using the procedures described in C-5000, C-6000, or C-7000 as applicable to the failure mode, determine the allowable flaw depth, $a_{allow}$, or the allowable applied stress $S_c$ or $S_a$, and the allowable flaw length limit $\ell_{allow}$.

(h) Using the critical flaw parameters $a_f$ and $\ell_f$, or the piping stresses, $\sigma_m$ and $\sigma_p$, apply the flaw evaluation criteria of C-2600 to determine the acceptability of the pipe for continued service.

C-1300 NOMENCLATURE

The following nomenclature is used.

- $a$ = general depth dimension of a flaw, in. (mm)
- $a_f$ = max. depth to which the flaw is calculated to grow by the end of the evaluation period, in. (mm)
- $a_{allow}$ = max. allowable flaw depth corresponding to the flaw length $\ell_f$, in. (mm)
- $A$ = pipe geometry factor used to calculate $Z$ load multiplier for ductile flaw extension, dimensionless
- $A_F$ = factor used to calculate fatigue crack growth rate parameter $S_{ENV}$ (in./cycles - sec)$^{-0.67}$ [(mm/cycle - s)$^{0.67}$]
- $c$ = half-length for an axial through-wall flaw, in. (mm)
- $C$ = scaling parameter in fatigue crack growth rate for austenitic steel in air, (in./cycle) $\left(\text{kpsi} \cdot \text{in.}\right)^{-3.3}$ [(mm/cycle) $\left(\text{MPa} \cdot \text{m}\right)^{-3.3}$]
- $C_2$ = SCC crack growth rate coefficient for $K_I$ dependent crack growth, in./hr (m/s) $\left(\text{MPa} \cdot \text{m}\right)^{-0.7}$
- $C_o$ = material constant in flaw growth equation, (in./cycle) $\left(\text{kpsi}\cdot\text{in.}\right)^{-0.7}$ [(mm/cycle) $\left(\text{MPa} \cdot \text{m}\right)^{-0.7}$]
- $C_T$ = scaling parameter to account for effect of temperature in fatigue crack growth rate (in./cycle) $\left(\text{kpsi}\cdot\text{in.}\right)^{-0.7}$ [(mm/cycle) $\left(\text{MPa} \cdot \text{m}\right)^{-0.7}$]
- $C_{1m}$ = orientation of a test specimen loaded in the circumferential direction with longitudinal crack plane orientation
- $CVN$ = Charpy V-notch absorbed energy, ft-lb (J)
- $D$ = pipe outside diameter, in. (mm)
- $da/dN$ = cyclic flaw growth rate, in./cycle (mm/cycle)
- $da/dt$ = flaw growth rate, in./hr (m/s)
- $E$ = Young's modulus, ksi (MPa)
- $E'$ = $E/(1 - \nu^2)$, ksi (MPa)
- $F_T$ = parameter for axial flaw stress intensity factor
- $F_m$ = parameter for circumferential flaw membrane stress intensity factor
- $F_{bt}$ = parameter for circumferential flaw bending stress intensity factor
- $F_{TW}$ = parameter for through-wall axial flaw stress intensity factor
- $J_{1mm}$ = measure of toughness at 1 mm of crack growth at the evaluation temperature (in.-lb/in.$^2$ (kJ/m$^2$))
- $J_{lc}$ = measure of toughness due to crack extension at the evaluation temperature, (in.-lb/in.$^2$ (kJ/m$^2$))
- $K_c$ = critical fracture toughness for the material, ksi/\sqrt{in.} (MPa/\sqrt{m})
- $K_I$ = Mode I stress intensity factor, ksi/\sqrt{in.} (MPa/\sqrt{m})
- $K_{lc}$ = static fracture toughness for crack initiation under plane strain conditions, ksi/\sqrt{in.} (MPa/\sqrt{m})
- $\Delta K_I$ = max. range of $K_I$ fluctuation during a transient, ksi/\sqrt{in.} (MPa/\sqrt{m})
- $K_{min}$ = min. stress intensity factor associated with transient stress range, $\Delta K$, ksi/\sqrt{in.} (MPa/\sqrt{m})
- $K_{max}$ = max. stress intensity factor associated with transient stress range, $\Delta K$, ksi/\sqrt{in.} (MPa/\sqrt{m})
- $K'_{r}$ = a component of screening criteria (SC), the ratio of the stress intensity factor to the material toughness, dimensionless
- $K_{im}$ = Mode I stress intensity factor for membrane loading, ksi/\sqrt{in.} (MPa/\sqrt{m})
- $K_{ib}$ = Mode I stress intensity factor for bending loading, ksi/\sqrt{in.} (MPa/\sqrt{m})
- $K_{ir}$ = stress intensity factor for residual stress, ksi/\sqrt{in.} (MPa/\sqrt{m})
- $K_{th}$ = threshold stress intensity factor for SCC, ksi/\sqrt{in.} (MPa/\sqrt{m})
There are two types, "eq." and "Eq." Which is better "eq." or "Eq."?

ARTICLE C-7000
FLAW EVALUATION FOR NONDUCTILE FRACTURE USING LEFM CRITERIA

C-7100 SCOPE

This Article provides the methodology for determining allowable flaw depths in flawed piping meeting the linear elastic fracture mechanics criteria of C-4200, when ductile crack extension does not occur prior to fracture. Solutions are given for both axial and circumferential flaws and are presented in the form of equations that shall be used with the material properties obtained in accordance with C-8310 or C-8320, for austenitic or ferritic materials, respectively. Applied stresses shall include residual stresses.

C-7200 EVALUATION PROCEDURES

A flowchart for the evaluation is given in Fig. C-7200-1, when the failure mode has been determined to be linear elastic fracture, using the procedures of C-4200. The allowable flaw depth, \( a_{\text{allow}} \), for each service level, shall be obtained by solving eq. (11) for the flaw depth, \( a \).

\[
K_f = \left[ \frac{J_{IC} E'}{1000} \right]^{0.5}
\]

where \( K_f \) contains the flaw depth, \( a \), and is defined for a circumferential flaw in C-7300 and for an axial flaw in C-7400. The allowable flaw depth shall be used in the acceptance criteria of C-2611 to determine the acceptability of the flawed pipe for continued service.

Conversely, eq. (11) may be rewritten as equivalent criteria in terms of the stress intensity factor.

\[
K_f \leq \left[ \frac{J_{IC} E'}{1000} \right]^{0.5} = K_c
\]

For this criterion, the end-of-evaluation-period flaw depth, \( a_p \), shall be used to determine \( K_f \) in C-7300 and C-7400.

C-7300 CIRCUMFERENTIAL FLAWS

The stress intensity factor for a circumferential flaw, including the appropriate structural factor, is given by the following:

\[
K_I = K_{Im} + K_{fb} + K_{fr}
\]

where

(U.S. Customary Units)

\[
K_{Im} = (SF_m)F_m \sigma_m \left( \frac{\pi a}{Q} \right)^{0.5}
\]

\[
K_{fb} = \left[ (SF_b) \sigma_b + \sigma_o \right] F_b \left( \frac{\pi a}{Q} \right)^{0.5}
\]

\[
K_{fr} = K_f \text{ from residual stresses at the flaw location}
\]

\( SF_m \) and \( SF_b \) = structural factors from C-2621

(SI Units)

\[
K_{Im} = (SF_m)F_m \sigma_m \left( \frac{\pi a}{1000} \right)^{0.5}
\]

\[
K_{fb} = \left[ (SF_b) \sigma_b + \sigma_o \right] F_b \left( \frac{\pi a}{1000} \right)^{0.5}
\]

The other terms are defined in C-4311. Residual stress shall be included with a structural factor of 1.0 in determining \( K_{fr} \). The allowable flaw depth, \( a_{\text{allow}} \), determined from eq. C-7200(12) and eq. C-7300(13) shall be used in the acceptance criteria of C-2611 to determine the acceptability of the flawed pipe for continued service.

C-7400 AXIAL FLAWS

The stress intensity factor for an axial flaw, including the appropriate structural factor, is given by the following:

\[
K_I = K_{Im} + K_{fr}
\]

where

(U.S. Customary Units)

\[
K_{Im} = (SF_m) F \sigma_h \left( \frac{\pi a}{Q} \right)^{0.5}
\]

\( \sigma_h = pR_m/t \)

(SI Units)

\[
K_{Im} = (SF_m) F \sigma_h \left[ \frac{\pi a}{1000Q} \right]^{0.5}
\]

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Table C-8321-2
Temperature for Onset of Upper-Shelf Behavior for Axial and Circumferential Flaws in Ferritic Steel Base Metals and Weldments

<table>
<thead>
<tr>
<th>Wall Thickness (in, mm)</th>
<th>Surface Flaws Temperature °F (°C)</th>
<th>Through-Wall Flaws Temperature °F (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤0.25 (6)</td>
<td>45 (-43)</td>
<td>69 (9)</td>
</tr>
<tr>
<td>0.375 (10)</td>
<td>4 (-20)</td>
<td>73 (23)</td>
</tr>
<tr>
<td>0.50 (13)</td>
<td>22 (-6)</td>
<td>86 (30)</td>
</tr>
<tr>
<td>0.625 (16)</td>
<td>35 (2)</td>
<td>94 (35)</td>
</tr>
<tr>
<td>0.75 (19)</td>
<td>43 (6)</td>
<td>104 (46)</td>
</tr>
<tr>
<td>1.00 (25)</td>
<td>52 (11)</td>
<td>110 (43)</td>
</tr>
<tr>
<td>1.25 (32)</td>
<td>58 (15)</td>
<td>114 (46)</td>
</tr>
<tr>
<td>1.50 (38)</td>
<td>63 (17)</td>
<td>118 (48)</td>
</tr>
<tr>
<td>1.75 (44)</td>
<td>66 (19)</td>
<td>121 (50)</td>
</tr>
</tbody>
</table>

GENERAL NOTES:
(a) This table is applicable to piping and portions of adjoining pipe fittings within a distance of \( R_{2} \) from the weld centerline. The weld geometry and weld-base-metal interface are defined in Fig. C-1100-1. Applicability of this table to wrought carbon steel pipe fittings is limited to those fittings that have been heat treated and subsequently normalized or annealed in accordance with the requirements of the material specification (e.g., Section II, Part A).
(b) The values of temperature in this table may be interpolated to determine temperatures for intermediate values of wall thickness.

used. In the absence of specific data, the upper-shelf temperature for ferritic piping steels shall be 200°F (95°C), or the upper-shelf temperatures in Table C-8321-2 may be used for flaws in wall thickness less than or equal to 2.0 in. (51 mm). A lower temperature may be used to define upper-shelf behavior when it is determined from valid heat-specific CVN tests.

C-8322 Toughness Properties for Axially Oriented Flaws

The toughness, \( J_{lc} \), in the CL direction shall be obtained directly from heat-specific experiments or from correlations with heat-specific CVN data or reasonable lower-bound CVN data. If heat-specific or reasonable lower-bound \( K_{lc} \) data for ferritic piping materials with specified minimum yield not greater than 40 ksi (280 MPa) are available for the CL direction, a conservative estimate for \( J_{lc} \) shall be determined from the following:

\[
J_{lc} = 1000 (K_{lc})^2 / E
\]

Alternatively, values for \( J_{lc} \) shall be obtained from Table C-8322-1. In the absence of specific data, the upper-shelf temperature for ferritic piping steels shall be 200°F (95°C), or the upper-shelf temperatures in Table C-8321-2 may be used for flaws in wall thickness less than or equal to 2.0 in. (51 mm). A lower temperature may be used to define upper-shelf behavior when determined from valid heat-specific CVN tests.

C-8330 OTHER PIPING MATERIALS

For other piping materials, including nonferrous alloys and cast austenitic stainless steel with high ferrite content, similar procedures may be used to establish \( J_{lc} \), \( K_{lc} \), or \( K_{lc} \). Material condition, testing parameters, test results, and toughness correlations shall be appropriate for the pipe material and flaw orientation under evaluation.

C-8400 FATIGUE CRACK GROWTH RATE

C-8410 Austenitic Steels

The fatigue crack growth behavior of austenitic stainless steels is affected by temperature, \( R \) ratio (\( K_{min}/K_{max} \)), and environment. Reference fatigue crack growth rates for air and water environments are given by the following:

(a) Reference fatigue crack growth behavior of cast and wrought austenitic stainless steels and their welds exposed to air environments (e.g., subsurface flaws) are given by eq. C-3210(a)(1) with \( n = 3.3 \) and

\[
C_{o} = CS \quad (16)
\]

where \( C \) is a scaling parameter to account for temperature and is given by

(U.S. Customary Units)

\[
C = 10\left[ -10.009 + 8.12 \times 10^{-4}T - 1.13 \times 10^{-6}T^2 + 1.02 \times 10^{-9}T^3 \right]
\]

(SI Units)

\[
C = 10\left[ -8.714 + 1.34 \times 10^{-3}T - 3.34 \times 10^{-6}T^2 + 5.95 \times 10^{-9}T^3 \right]
\]

where \( T \) is the metal temperature in °F (°C) [for \( T \leq 800°F \) (430°C)], and \( S \) is a scaling parameter to account for \( R \) ratio and is given by:

Table C-8322-1
Material Properties for Ferritic Steel Base Metals and Weldments — Axial Flaws

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_{y} )</td>
<td>( J_{lc} )</td>
</tr>
<tr>
<td>27.1 (187)</td>
<td>300 (53)</td>
</tr>
</tbody>
</table>

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\[ S = 1.0 \text{ when } R \leq 0 \]
\[ = 1.0 + 1.8R \text{ when } 0 < R \leq 0.79 \]
\[ = -43.35 + 57.97R \text{ when } 0.79 < R < 1.0 \]

The scaling constant \( C_0 \) from eq. (16) produces fatigue crack growth rates in the units of in./cycle (mm/cycle) when \( \Delta K_i \) is in the units of ksi\( \sqrt{\text{in.}} \) (MPa\( \sqrt{\text{m}} \)) and is intended for use when data from the product form are not available. Reference fatigue crack growth rate curves using [Eq. C-3210(a)(1)] and Eq. (16) are provided in Fig. C-8410-1 (Fig. C-8410-1M).

(b) Reference fatigue crack growth rates for austenitic stainless steels exposed to water environments are in the course of preparation.

C-8411 Alloy 600

The fatigue crack growth rate of alloy 600 material is affected by temperature, \( R \) ratio, load rise time, and environment. Reference fatigue crack growth rates for PWR and BWR water environments, as well as for air environment, are given by the following. Reference curves for a temperature of 608°F (320°C) are provided in Fig. C-8410-2 (Fig. C-8410-2M).

(a) The reference fatigue crack growth rate of alloy 600 exposed to water environments is given by Eq. C-3210(a)(1) with \( n = 4.1 \) and

\[ C_0 = C_F S_R S_{ENV} \quad \text{(17)} \]

where

\[ S_R = (1 - 0.32R)^{-2.2} \]
\[ S_{ENV} = 1 + AE[C_F S_R (\Delta K_i)^n]^{-0.67} \tau^0.67 \]

and

(U.S. Customary Units)

\[ C_F = 2.606 \times 10^{-12} + 7.060 \times 10^{-15}T \]
\[-3.080 \times 10^{-17}T^2 + 4.327 \times 10^{-20}T^3 \]
\[ A_E = 5.155 \times 10^{-6} \text{ (in./cycles – sec)}^{-0.67} \]

(SI Units)

\[ C_F = 4.835 \times 10^{-11} + 1.622 \times 10^{-13}T \]
\[-1.490 \times 10^{-15}T^2 + 4.355 \times 10^{-18}T^3 \]
\[ A_E = 4.503 \times 10^{-5} \text{ (mm/cycles – s)}^{-0.67} \]

where

\( A_E \) = factor used to calculate fatigue crack growth rate environment parameter \( S_{ENV} \)
\( C_F \) = scaling parameter to account for temperature
\( n \) = fatigue crack growth rate exponent
\( R = R \) ratio \( = K_{min}/K_{max} \)
\( S_{ENV} \) = scaling parameter to account for reactor water environment
\( S_R \) = scaling parameter to account for \( R \) ratio
\( T \) = metal temperature in °F (°C)
\( \Delta K_i \) = maximum range of \( K_i \) fluctuation during a transient in ksi\( \sqrt{\text{in.}} \) (MPa\( \sqrt{\text{m}} \))
\( \tau \) = load rise time in s

When \( \tau \) exceeds 30 s, \( \tau \) shall be set equal to 30 s. The scaling factor \( C_0 \) in eq. (17) produces fatigue crack growth rate in units of in./cycle (mm/cycle) when \( \Delta K_i \) is in units of ksi\( \sqrt{\text{in.}} \) (MPa\( \sqrt{\text{m}} \)).

(b) The reference fatigue crack growth rate of alloy 600 exposed to air environment (e.g., subsurface flaws) is given by Eq. C-3210(a)(1), with \( n = 4.1 \), and \( C_0 \) calculated in accordance with (a) above with \( S_{ENV} = 1 \).

C-8420 FERRITIC STEELS

The fatigue crack growth behavior of ferritic steels is affected by temperature, \( R \) ratio \( (K_{min}/K_{max}) \), and environment. Reference fatigue crack growth rates for air and water environments are in the course of preparation. The reference fatigue crack growth curves for ferritic vessel steels in A-4300 may be used.

C-8430 OTHER MATERIALS

The fatigue crack growth rates for materials not covered by C-8410 or C-8420 may be obtained from other sources. The growth rate curve should represent conservative values of fatigue crack growth rates for the appropriate environment, cyclic loading, and \( R \) ratio.

C-8500 STRESS CORROSION CRACKING GROWTH RATE

C-8510 ALLOY 600 AND ASSOCIATED WELD MATERIALS

The SCC crack growth rate of alloy 600 and associated weld materials is a function of the material condition, temperature, environment, and stress intensity factor due to sustained loading. Reference SCC crack growth rates for PWR environment are given in C-8511 and for BWR environment in C-8512.

C-8511 Alloy 600 and Associated Weld Materials

Alloys 82, 182, and 132 in PWR Environment

The rate of stress corrosion cracking in a PWR environment is given by:
C-3000 STRESS CORROSION CRACKING
C-3000 ALUMINUM AND ASSOCIATED METALS

MATERIALS

In addition to 5000 series aluminum alloys, C-3000 can also be used in the following alloys: 7000 series, 6000 series, and 5000 series.

C-3000 is available in hard and soft temper.

Chemical composition of C-3000:

- Aluminum: 99.5%
- Copper: 0.3%
- Magnesium: 0.7%
- Silicon: 0.5%
- Iron: 0.2%
- Manganese: 0.1%
- Other: 0.1%

C-3000 is subjected to stress corrosion cracking at temperatures above 150°F (65°C) in seawater.

Applications of C-3000:

- Marine equipment
- Offshore structures
- Steam power plant equipment

C-3000 is also used in the following applications:

- Offshore structures
- Boats and yachts
- Marine equipment
ARTICLE H-4000
FAILURE ASSESSMENT DIAGRAM PROCEDURE

H-4100 SCOPE

This Article describes the failure assessment diagram procedure for evaluation of flaws in ferritic and austenitic piping. The procedure requires a failure assessment diagram and failure assessment point coordinates. End-of-evaluation-period flaw dimensions shall be used.

H-4200 STRUCTURAL FACTORS

Evaluation of flaws using the failure assessment diagram procedure requires application of structural factors. The structural factors $SF_m$ and $SF_b$ applied to primary membrane stresses and primary bending stresses, respectively, are given in Table H-4200-1 for circumferential flaws and Table H-4200-2 for axial flaws.

H-4300 FAILURE ASSESSMENT DIAGRAMS

Figures H-4300-1 and H-4300-2 give failure assessment diagrams for ferritic piping and austenitic piping, respectively. These figures apply to piping having

(a) part-through-wall circumferential flaws, under any combination of primary membrane, primary bending, and expansion stresses (see Fig. H-4400-1); or

(b) part-through-wall axial flaws under internal pressure (see Fig. H-4400-2).

Figures H-4300-1 and H-4300-2 apply for circumferential flaws of depths up to 75% of the pipe wall thickness, and for axial flaws of depths up to 75% of the pipe wall thickness and lengths up to $t_{allow}$, where $t_{allow}$ is given by the limit load stability condition for through-wall flaws:

$$t_{allow} = 1.58(R_t)^{1/2} \left[ \frac{(t_f - t_h)}{t_h} \right]^{1/2}$$

For axial flaws, the failure assessment diagrams shown in Figs. H-4300-1 and H-4300-2 have a vertical cutoff for upper bound limits on $S_n$. For circumferential flaws, the upper limit on $S_n$ is established by limits on primary stresses. The procedures for calculating the values of the cutoff and limits on primary stress are given in H-4400. The failure assessment diagrams are limited to $R/t$ less than or equal to 20.

H-4400 FAILURE ASSESSMENT DIAGRAM PRIMARY STRESS LIMITS

Limits on the primary stresses in the failure assessment diagram analysis are provided by the following:

<table>
<thead>
<tr>
<th>Service Level</th>
<th>Membrane Stress, $SF_m$</th>
<th>Bending Stress, $SF_b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.7</td>
<td>2.3</td>
</tr>
<tr>
<td>B</td>
<td>2.4</td>
<td>2.0</td>
</tr>
<tr>
<td>C</td>
<td>1.8</td>
<td>1.6</td>
</tr>
<tr>
<td>D</td>
<td>1.3</td>
<td>1.4</td>
</tr>
</tbody>
</table>
Table H-4200-2
Specified Structural Factors for Axial Flaws

<table>
<thead>
<tr>
<th>Service Level</th>
<th>Membrane Stress, $S_{F_m}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.7</td>
</tr>
<tr>
<td>B</td>
<td>2.4</td>
</tr>
<tr>
<td>C</td>
<td>1.8</td>
</tr>
<tr>
<td>D</td>
<td>1.3</td>
</tr>
</tbody>
</table>

(a) direct application of limits on primary stresses for part-through-wall circumferential flaws (see Fig. H-4400-1) under any combination of primary membrane and primary bending stresses or
(b) application of a vertical cutoff on the failure assessment diagram for part-through-wall axial flaws (see Fig. H-4400-2) under internal pressure

**H-4410 CIRCUMFERENTIAL FLAW PRIMARY STRESS LIMITS**

(a) The applied primary membrane stress shall satisfy the following equation:

$$\sigma_m \leq \sigma_{mf} \frac{S_{F_m}}{S_{F_b}}$$

where $S_{F_m}$ is the structural factor on primary membrane stress specified in Table H-4200-1 and

$$\sigma_{mf} = \sigma_f \left[ 1 - \frac{a}{t} \frac{\theta}{\pi} - 2\psi/\pi \right]$$

$$\psi = \arcsin \left[ 0.5 \left( \frac{a}{t} \right) \sin \theta \right]$$

(b) The applied primary bending stress shall satisfy the following equation:

$$\sigma_b \leq \sigma_{bf} \frac{S_{F_b}}{S_{F_m}} - \sigma_m \left( 1 - \frac{1}{S_{F_m}} \right)$$

where $S_{F_m}$ and $S_{F_b}$ are the structural factors on primary membrane stress and primary bending stress, respectively, specified in Table H-4200-1. For circumferential flaws not penetrating the compressive region of the pipe cross-section, $\theta + \beta \leq \pi$, and

$$\sigma_{bf} = 2\sigma_f \pi \left[ 2 \sin \beta - \left( \frac{a}{t} \right) \sin \theta \right]$$

where

$$\beta = \frac{1}{2} \left[ \pi - \left( \frac{a}{t} \right) \theta - \pi \sigma_m / \sigma_f \right]$$

For longer flaws penetrating the compressive region of the pipe cross-section, $\theta + \beta > \pi$, and

$$\sigma_b = 2\sigma_f \pi \left( 2 - \frac{a}{t} \right) \sin \beta$$

where

$$\beta = \pi / \left( 2 - \frac{a}{t} \right) \left[ 1 - \frac{a}{t} - \sigma_m / \sigma_f \right]$$

**H-4420 AXIAL FLAW CUTOFF**

For axial flaws in piping under internal pressure, the limit load cutoff for $S_p$ is given by
\[
S_T = \frac{P_T}{P_0}
\]

where
\[
P_0 = \left( \frac{2}{\sqrt{3}} \right) \left( \frac{t}{R_1} \right) \left[ 1 - \frac{a}{t} + \left( \frac{a}{t} f(z) \right) \sigma_y \right]
\]
\[
f(z) = (1 + 1.61z)^{0.5}
\]
\[
z = 0.1542 \frac{\epsilon^2}{\left[ t \left( \frac{R_k}{t} + 0.5 \right) \right]}
\]
\[
P_T = \left( \frac{t}{R_1} \right) \sigma_T \left[ \left( 1 - \frac{a}{t} \right) / \left( 1 - \frac{a}{t} / M_2 \right) \right]
\]
\[
M_2 = \left( 1 + \frac{1.61 \epsilon^2}{(4Rt)} \right)^{0.5}
\]

**H-4500 FAILURE ASSESSMENT POINT COORDINATES**

The failure assessment point coordinates, \((S_T', K_T')\) shall be calculated for the end-of-evaluation-period flaw dimensions and for stresses at the location of, and normal to, the flaw, using the \(J_T\) resistance curve data when ductile flaw extension at upper-shelf temperatures may occur prior to reaching limit load, or using \(J_{te}\) fracture toughness data at transition or lower-shelf temperatures.

**H-4510 CIRCUMFERENTIAL FLAWS**

The equation necessary to calculate the failure assessment point coordinates \((S_T', K_T')\) for part-through-wall circumferential flaws for a specified amount of ductile flaw extension, \(\Delta a\), is given in (a). When the temperature is in the transition or lower-shelf region, \(J_T\) shall be replaced by \(J_{te}\) and \(\Delta a\) shall be zero.

(a) The coordinate \(S_T'\) is given by the following equation when the primary membrane stress, \(\sigma_{m'}\), is not zero:
where $S_F^m$ is the structural factor on primary membrane stress specified in Table H-4200-1, $\sigma'_m$ is recalculated for each value of $\Delta a$, and

$$\sigma'_m = \sigma_m \psi \Gamma_m$$

$$\psi = \frac{-\pi \sigma_b}{8 \sigma_m} + \left[ \frac{\pi \sigma_b}{8 \sigma_m} \right] + 1$$

$$\Gamma_m = \frac{(R_2^2 - R_c^2)(1 - \theta/\pi) (R_2^2 - R_1^2)}{(R_2^2 - R_1^2)}$$

$$R_c = R_1 + a + \Delta a$$

where $\Gamma_m$ is recalculated for each value of $\Delta a$. When the primary membrane stress, $\sigma_m$, is zero, the coordinate $S_F^r$ is given by

$$S_F^r = \pi (S_F^b) \sigma_b / \left[ 4 \sigma_m \Gamma_m \right]$$

where $S_F^b$ is the structural factor on primary bending stress specified in Table H-4200-1, and $\Gamma_m$ is recalculated for each value of $\Delta a$.

(b) The coordinate $K_F^r$ is given by

$$K_F^r = \left( I_e / I_B \right)^{0.5}$$

for any value of $\sigma_m$, where $I_e$ and $I_B$ are also recalculated for each value of $\Delta a$. The linear elastic J-integral is given by

$$J_e = 1000 K_F^2 / E$$

where

(U.S. Customary Units)

$$K_F = \left( S_F^m \sigma_m F_m (\pi a)^{0.5} + \left[ S_F^b \sigma_b + \sigma_y \right] F_b (\pi a')^{0.5} + K_{fr} \right)$$

(SI Units)

$$K_F = \left( S_F^m \sigma_m F_m (\pi a / 1000)^{0.5} + \left[ S_F^b \sigma_b + \sigma_y \right] F_b (\pi a' / 1000)^{0.5} + K_{fr} \right)$$
\[ F_m = 1.1 + \left( \frac{a'}{t} \right) 0.15241 + 16.722 \left( \frac{a'}{t} \right) \left( \frac{\theta}{\pi} \right)^{0.855} - 14.944 \left( \frac{a'}{t} \right) \left( \frac{\theta}{\pi} \right) - 5.846 \left( \frac{a'}{t} \right) \left( \frac{\theta}{\pi} \right)^{0.565} - 2.8329 \left( \frac{a'}{t} \right) \left( \frac{\theta}{\pi} \right) \]

\[ R_b = 1.1 + \left( \frac{a'}{t} \right) - 0.09697 + 5.0057 \left( \frac{a'}{t} \right) \left( \frac{\theta}{\pi} \right)^{0.565} - 2.8329 \left( \frac{a'}{t} \right) \left( \frac{\theta}{\pi} \right) \]

\[ a' = a + \Delta a \]

In the above equations, \( a' \) is updated after each increment of ductile flaw extension, while \( \theta \) is fixed at its end-of-evaluation-period value. Residual stresses shall be included with a structural factor of 1.0.

**H-4520 AXIAL FLAWS**

Failure assessment point coordinates \( (S_p', K_p') \) for part-through-wall axial flaws with a specified amount of ductile flaw extension, \( \Delta a \), are given below. When the temperature is in the transition or lower-shelf region, \( J_R \) shall be replaced by \( J_{lo} \) and \( \Delta a \) shall be zero.

(a) The coordinate \( S_p' \) is given by

\[ S_p' = \left( \frac{SF_m}{P_0} \right) \]

where \( SF_m \) is the structural factor on primary membrane stress specified in Table H-4200-2, and \( P_0 \) is recalculated for each value of \( \Delta a \).

\[ P_0 = \left( \frac{2}{\sqrt{3}} \right) \left( \frac{t}{R_1} \right) \left[ 1 - \frac{a'}{t} + \left( \frac{a'}{t} / f(z) \right) \sigma_y \right] \]

\[ f(z) = (1 + 1.612)^{0.5} \]

\[ z = 0.1542 \left( \frac{\varepsilon}{t} / \left[ 0.5 \left( R_1 / t + 0.5 \right) \right] \right) \]

\[ a' = a + \Delta a \]

(b) The coordinate \( K_p' \) is given by

\[ K_p' = \left( \frac{J_e}{J_R} \right)^{0.5} \]

where \( J_e \) and \( J_R \) are calculated for each value of \( \Delta a \). The linear elastic J-integral is given by

\[ J_e = 1000 \frac{K_p'}{E'} \]

and

(U.S. Customary Units)

\[ K_i = \left( \frac{SF_m}{P} \right) \left( \frac{R_1}{t} \right) F_1 \left( \frac{a'}{t} Q \right)^{0.5} + K_{fr} \]

(SI Units)

\[ K_i = \left( \frac{SF_m}{P} \right) \left( \frac{R_1}{t} \right) F_1 \left( \frac{a'}{t} / 1000Q \right)^{0.5} + K_{fr} \]

\[ Q = 1 + 4.593(a / t)^{1.65} \]

\[ F_1 = 0.97 \left[ M_1' + M_2' \left( \frac{a'}{t} \right)^2 + M_3' \left( \frac{a'}{t} \right)^4 \right] f_e \]

\[ f_e = \left[ \frac{R_2^2 + R_1^2}{R_2^2 - R_1^2} \right] \left[ 1 - 0.5 \left( a / t \right)^{0.5} \right] \]

\[ M_1' = 1.13 - 0.18 (a / \ell) \]

\[ M_2' = -0.54 + 0.445 / (0.1 + a / \ell) \]
\[ M_3' = 0.5 - \frac{1}{(0.65 + 2a/t)} + 14(1 - 2a/t)^{24} \]

In the preceding equations, \( a' \) is updated after each increment of ductile flaw extension, while \( a/t \) is fixed at its end-of-evaluation-period value. Residual stresses shall be included with a structural factor of 1.0.
NONMANDATORY APPENDIX G
FRACTURE TOUGHNESS CRITERIA FOR PROTECTION AGAINST FAILURE

ARTICLE G-1000
INTRODUCTION

This Appendix presents a procedure for obtaining the allowable loadings for ferritic pressure retaining materials in components. This procedure is based on the principles of linear elastic fracture mechanics. At each location being investigated a maximum postulated flaw is assumed. At the same location the mode I stress intensity factor, $K_I$, is produced by each of the specified loadings as calculated and the summation of the $K_I$ values is compared to a reference value $K_{IC}$ which is the highest critical value of $K_I$ that can be ensured for the material and temperature involved. Different procedures are recommended for different components and operating conditions.
G-2100  GENERAL REQUIREMENTS

G-2110  REFERENCE CRITICAL STRESS INTENSITY FACTOR

(a) Figure G-2210-1 is a curve showing the relationship that can be conservatively expected between the critical, or reference, stress intensity factor $K_{fc}$ ksi $\sqrt{\text{in.}}$ (MPa $\sqrt{\text{m}}$) and a temperature which is related to the reference nil-ductility temperature $RT_{NDT}$ determined in NB-2331. This curve is based on the lower bound of static critical $K_{I}$ values measured as a function of temperature on specimens of SA-533 Grade B Class 1, and SA-508-1, SA-508-2, and SA-508-3 steel. No available data points for static tests fall below the curve. An analytical approximation to the curve is:

(U.S. Customary Units)

$$K_{fc} = 33.2 + 20.734 \exp[0.02(T - RT_{NDT})]$$

(SI Units)

$$K_{fc} = 36.5 + 22.783 \exp[0.036(T - RT_{NDT})]$$

Unless higher $K_{fc}$ values can be justified for the particular material and circumstances being considered, Fig. G-2210-1 may be used for ferritic steels which meet the requirements of NB-2331 and which have a specified minimum yield strength at room temperature of 50 ksi (350 MPa) or less.

(b) For materials which have specified minimum yield strengths at room temperature greater than 50 ksi (350 MPa) but not exceeding 90 ksi (620 MPa), Fig. G-2210-1 may be used provided fracture mechanics data are obtained on at least three heats of the material on a sufficient number of specimens to cover the temperature range of interest, including the weld metal and heat-affected zone, and provided that the data are equal to or above the curve of Fig. G-2210-1. These data shall be documented by the Owner. Where these materials of higher yield strengths (specified minimum yield strength greater than 50 ksi (350 MPa) but not exceeding 90 ksi (620 MPa) are to be used in conditions where radiation may affect the material properties, the effect of radiation on the $K_{fc}$ curve shall be determined for the material. This information shall be documented by the Owner.

G-2120  MAXIMUM POSTULATED DEFECT

The postulated defects used in this recommended procedure are sharp, surface defects oriented axially for plates, forgings, and axial welds, and circumferentially for circumferential welds. For section thicknesses of 4 in. to 12 in. (100 mm to 300 mm), the postulated defects have a depth of one-fourth of the section thickness and a length of $1\frac{1}{2}$ times the section thickness. Defects are postulated at both the inside and outside surfaces. For sections greater than 12 in. (300 mm) thick, the postulated defect for the 12 in. (300 mm) section is used. For sections less than 4 in. (100 mm) thick, the 1 in. (25 mm) deep defect is conservatively postulated. Smaller defect sizes $^{24}$ may be used on an individual case basis if a smaller size of maximum postulated defect can be ensured. Due to the structural factors recommended here, the prevention of nonductile fracture is ensured for some of the most important situations even if the defects were to be about twice as large in linear dimensions as this postulated maximum defect.

G-2200  LEVEL A AND LEVEL B SERVICE LIMITS

G-2210  SHELLS AND HEADS REMOTE FROM DISCONTINUITIES

G-2211  Recommendations

The assumptions of this Subarticle are recommended for shell and head regions during Level A and B Service Limits.

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for an inside surface flaw

\[
RT_{NDT} = RT_{NDT(0)} + \Delta RT_{NDT}\text{ and is the reference nil ductility temperature adjusted for irradiation effects at the maximum depth of the postulated quarter thickness flaw stipulated in G-2214.3, }{}^{\circ}\text{F}
\]

\[
RT_{NDT(0)} = \text{equivalent to the unirradiated } RT_{NDT}\text{ calculated in accordance with NB-2300, }{}^{\circ}\text{F}
\]

\[
\Delta RT_{NDT} = \text{an adjustment for irradiation effects, }{}^{\circ}\text{F}
\]

\[
T = \text{temperature at the maximum depth of the postulated quarter thickness flaw stipulated in G-2214.3, }{}^{\circ}\text{F}
\]

(SI Units)

\[
T = RT_{NDT} + 33 + \ln\left[\left(\frac{K_{fn} + K_B - 36.5}{22.783}\right)\right]/0.036
\]

for an outside surface flaw or

\[
T = RT_{NDT} + 33 + \ln\left[\left(\frac{K_{fn} - 36.5}{22.783}\right)\right]/0.036
\]

for an inside surface flaw

\[
RT_{NDT} = RT_{NDT(0)} + \Delta RT_{NDT}\text{ and is the reference nil ductility temperature adjusted for irradiation effects at the maximum depth of the postulated quarter thickness flaw stipulated in G-2214.3, }{}^{\circ}\text{C}
\]

\[
RT_{NDT(0)} = \text{equivalent to the unirradiated } RT_{NDT}\text{ calculated in accordance with NB-2300, }{}^{\circ}\text{C}
\]

\[
\Delta RT_{NDT} = \text{an adjustment for irradiation effects, }{}^{\circ}\text{C}
\]

\[
T = \text{temperature at the maximum depth of the postulated quarter thickness flaw stipulated in G-2214.3, }{}^{\circ}\text{C}
\]

The operational pressure-temperature limits are based on the temperature at the reactor coolant inlet temperature, which is assumed to equal the temperature at the vessel inner surface. Figures G-2214-1 (Fig. G-2214-1M) and G-2214-2 can be used to determine the temperature at the vessel inner surface corresponding to the temperature at the maximum depth of the postulated quarter thickness flaw stipulated in G-2214.3.

\[
\Delta RT_{NDT}\text{ is determined from plant-specific surveillance data, or the irradiation degradation model used to compute the risk-informed allowable pressure [see eq. G-2216 (2)], or other irradiation degradation models acceptable to the regulatory authority having jurisdiction at the plant site.}
\]

**G-2520 HYDROSTATIC LEAK TEST HEAT-UP AND COOL-DOWN ALLOWABLE PRESSURE**

For heat-up and cool-down rates not to exceed 40°F/hr (22°C/hr), the allowable pressure as a function of temperature during hydrostatic leak test heat-up or cool-down shall be determined using the procedure in G-2216

(U.S. Customary Units)

\[
p = \{33.2 + 20.734 \exp [0.02(T - RT_{NDT} - 60)] - K_B\} \times t/R_i \times 1/M_{in}
\]

where

\[
p = \text{pressure (ksi)}
\]

\[
RT_{NDT} = RT_{NDT(0)} + \Delta RT_{NDT}\text{ and is the reference nil ductility temperature adjusted for irradiation effects at the maximum depth of the postulated quarter thickness flaw stipulated in G-2214.3, }{}^{\circ}\text{F}
\]

\[
RT_{NDT(0)} = \text{equivalent to the unirradiated } RT_{NDT}\text{ calculated in accordance with NB-2300, }{}^{\circ}\text{F}
\]

\[
\Delta RT_{NDT} = \text{an adjustment for irradiation effects, }{}^{\circ}\text{F}
\]

\[
T = \text{temperature at the maximum depth of the postulated quarter thickness flaw stipulated in G-2214.3, }{}^{\circ}\text{F}
\]

(SI Units)

\[
p = \{36.5 + 22.783 \exp [0.036(T - RT_{NDT} - 33)] - K_B\} \times t/R_i \times 1/M_{in}
\]

where

\[
p = \text{pressure (MPa)}
\]
\[ RT_{NDT} = RT_{NDT(0)} + \Delta RT_{NDT} \] and is the reference nil ductility temperature adjusted for irradiation effects at the maximum depth of the postulated quarter thickness flaw stipulated in G-2214.3, °C

\[ RT_{NDT(0)} = \text{equivalent to the unirradiated } RT_{NDT} \text{ calculated in accordance with NB-2300, °C} \]

\[ \Delta RT_{NDT} = \text{an adjustment for irradiation effects, °C} \]

\[ T = \text{temperature at the maximum depth of the postulated quarter thickness flaw stipulated in G-2214.3, °C} \]

\[ K_b \text{ is as stipulated in G-2214.3, and } t, R_b \text{ and } M_m \text{ are as stipulated in G-2214.1. The evaluation is to be performed for all materials and locations as described in G-2215.} \]

The operational pressure-temperature limits are based on the temperature at the reactor coolant inlet temperature, which is assumed to equal the temperature at the vessel inner surface. Figures G-2214-1 (Fig. G-2214-1M) and G-2214-2 can be used to determine the temperature at the vessel inner surface corresponding to the temperature at the maximum depth of the postulated quarter thickness flaw stipulated in G-2214.3.

\[ \Delta RT_{NDT} \text{ is determined from plant-specific surveillance data, or the irradiation degradation model used to compute the risk-informed allowable pressure [see eq. G-2216(2)], or other irradiation degradation models acceptable to the regulatory authority having jurisdiction at the plant site.} \]
ARTICLE G-3000
PIPING, PUMPS, AND VALVES

G-3100 GENERAL REQUIREMENTS

In the case of the materials other than bolting used for piping, pumps, and valves for which impact tests are required (NB-2311), the tests and acceptance standards of Section III, Division 1 are considered to be adequate to prevent nonductile failure under the loadings and with the defect sizes encountered under Levels A and B Service Limits and testing conditions. Level C and Level D Service Limits should be evaluated on an individual case basis (G-2300).
ARTICLE G-3000
Piping, Pumps, and Valves

G-3000 GENERAL REQUIREMENTS

In the case of new or existing water systems, the piping system shall be designed to provide an adequate water supply for all uses. The system shall be of a type that can be easily maintained and repaired. The system shall be designed to prevent contamination of the water supply. The system shall be equipped with appropriate control devices to ensure safe operation. The system shall be tested periodically to ensure compliance with the design requirements.
G-2212 Material Fracture Toughness

G-2212.1 Reference Critical Stress Intensity Factor for Material. The $K_{ic}$ values of Fig. G-2210-1 (Fig. G-2210-1M) are recommended.

G-2212.2 Irradiation Effects. Subarticle A-4400 of Appendix A is recommended to define the change in reference critical stress intensity factor due to irradiation.

G-2213 Maximum Postulated Defects

The recommended maximum postulated defects are described in G-2120.

G-2214 Calculated Stress Intensity Factors

G-2214.1 Membrane Tension. The $K_I$ corresponding to membrane tension for the postulated axial defect of G-2120 is $K_{Im} = M_m \times (pR_t / t)$, where $M_m$ for an inside axial surface flaw is given by

(U.S. Customary Units)

$M_m = 1.85$ for $t < 4$ in.

$M_m = 0.926 \sqrt{t}$ for $4$ in. $\leq t \leq 12$ in.

$M_m = 3.21$ for $t > 12$ in.

(SI Units)

$M_m = 0.296$ for $t < 102$ mm

$M_m = 0.0293 \sqrt{t}$ for $102$ mm $\leq t \leq 305$ mm

$M_m = 0.51$ for $t > 305$ mm

Similarly, $M_m$ for an outside axial surface flaw is given by

![Figure G-2210-1](image)

$1$ ksi-$\sqrt{\text{in.}} = 1.1$ MPa-$\sqrt{\text{m}}$
(U.S. Customary Units)
\[ M_m = 1.77 \text{ for } t < 4 \text{ in.} \]
\[ M_m = 0.893 \sqrt{t} \text{ for } 4 \text{ in.} \leq t \leq 12 \text{ in.} \]
\[ M_m = 3.09 \text{ for } t > 12 \text{ in.} \]

(SI Units)
\[ M_m = 0.285 \text{ for } t < 102 \text{ mm} \]
\[ M_m = 0.0282 \sqrt{t} \text{ for } 102 \text{ mm} \leq t \leq 305 \text{ mm} \]
\[ M_m = 0.493 \text{ for } t > 305 \text{ mm} \]

where

- \( p \) = internal pressure, ksi (MPa)
- \( R_i \) = vessel inner radius, in. (mm)
- \( t \) = vessel wall thickness, in. (mm)

The \( K_f \) corresponding to membrane tension for the postulated circumferential defect of G-2120 is \( K_{im} = M_m \times \left( \frac{p R_i}{t} \right) \), where \( M_m \) for an inside or an outside circumferential surface defect is given by

(U.S. Customary Units)
\[ M_m = 0.89 \text{ for } t < 4 \text{ in.} \]
\[ M_m = 0.443 \sqrt{t} \text{ for } 4 \text{ in.} \leq t \leq 12 \text{ in.} \]
\[ M_m = 1.53 \text{ for } t > 12 \text{ in.} \]

(SI Units)
\[ M_m = 0.141 \text{ for } t < 102 \text{ mm} \]
\[ M_m = 0.0140 \sqrt{t} \text{ for } 102 \text{ mm} \leq t \leq 305 \text{ mm} \]
\( M_m = 0.245 \) for \( t > 3.05 \) mm

**G-2214.2 Bending Stress.** The \( K_t \) corresponding to bending stress for postulated axial or circumferential defect of G-2120 is \( K_{tb} = M_b \times \) maximum bending stress, where \( M_b \) is two-thirds of \( M_m \) for the axial defect.

**G-2214.3 Radial Thermal Gradient.** The maximum \( K_t \) produced by a radial thermal gradient for a postulated axial or circumferential inside surface defect of G-2120 is

(U.S. Customary Units)
\[
K_{tr} = 0.953 \times 10^{-3} \times CR \times t^{2.5}
\]

(SI Units)
\[
K_{tr} = 0.579 \times 10^{-6} \times CR \times t^{2.5}
\]

where \( CR \) is the cooldown rate in \( ^\circ F/\text{hr} \) (\( ^\circ C/\text{hr} \)), \( t \) is the thickness in in. (mm), and \( K_{tr} \) is in ksi \( \sqrt{\text{in}} \) (MPa \( \sqrt{\text{m}} \)) or, for a postulated axial or circumferential outside surface defect

(U.S. Customary Units)
\[
K_{tr} = 0.753 \times 10^{-3} \times HU \times t^{2.5}
\]

(SI Units)
\[
K_{tr} = 0.458 \times 10^{-6} \times HU \times t^{2.5}
\]

where \( HU \) is the heatup rate in \( ^\circ F/\text{hr} \) (\( ^\circ C/\text{hr} \)).

The through-wall temperature difference associated with the maximum thermal \( K_t \) can be determined from Fig. G-2214-1. The temperature at any radial distance from the vessel surface can be determined from Fig. G-2214-2 for the maximum thermal \( K_t \).

(a) The maximum thermal \( K_t \) and the temperature relationship in Fig. G-2214-1 are applicable only for the conditions in (1) and (2).

(1) An assumed shape of the temperature gradient is approximately as shown in Fig. G-2214-2.

(2) The temperature change starts from a steady state condition and has a rate, associated with startup and shutdown, less than about 100\( ^\circ F/\text{hr} \) (56\( ^\circ C/\text{hr} \)). The results would be overly conservative if applied to rapid temperature changes.

(b) Alternatively, the \( K_t \) for radial thermal gradient can be calculated for any thermal stress distribution at any specified time during cooldown for a \( 1/4 \)-thickness axial or circumferential surface defect.

For an inside surface defect during cooldown

(U.S. Customary Units)
\[
K_{tr} = \left( 1.0359C_0 + 0.6322C_1 + 0.4753C_2 + 0.3855C_3 \right) \sqrt{\pi a}
\]

(SI Units)
\[
K_{tr} = \left( 0.2259C_0 + 0.1378C_1 + 0.1036C_2 + 0.08405C_3 \right) \sqrt{\pi a}
\]

For an outside surface defect during heatup

(U.S. Customary Units)
\[
K_{tr} = \left( 1.0433C_0 + 0.630C_1 + 0.481C_2 + 0.401C_3 \right) \sqrt{\pi a}
\]

(SI Units)
\[
K_{tr} = \left( 0.227C_0 + 0.137C_1 + 0.105C_2 + 0.0874C_3 \right) \sqrt{\pi a}
\]

The coefficients \( C_0, C_1, C_2, \) and \( C_3 \) are determined from the thermal stress distribution at any specified time during the heatup or cooldown using
\[
o(x) = C_0 + C_1(x/a) + C_2(x/a)^2 + C_3(x/a)^3
\]

where \( x \) is a dummy variable that represents the radial distance, in. (mm), from the appropriate (i.e., inside or outside) surface and \( a \) is the maximum crack depth, in.
Figure G-2214-1

\[ \Delta T_w = \frac{K_I}{M_I} \]

where

\[ \Delta T_w = \text{temperature difference through the wall} \text{ °F} \]

\[ K_I = \text{stress intensity factor, ksi } \sqrt{\text{in.}} \]

Curve for \( \alpha = 0.7 \times 10^{-6}, E = 29.2 \times 10^6 \text{ psi, } \nu = 0.3 \)

Crack Depth = Wall Thickness/4

Crack Depth = Wall Thickness/8

Wall Thickness, in.

G-2215 Allowable Pressure

The equations given in this Subarticle provide the basis for determination of the allowable pressure at any temperature at the depth of the postulated defect during Service Conditions for which Level A and Level B Service Limits are specified. In addition to the conservatism of these assumptions, it is recommended that a factor of 2 be applied to the calculated \( K_I \) values produced by primary stresses. In shell and head regions remote from discontinuities, the only significant loadings are: (1) general primary membrane stress due to pressure; and (2) thermal stress due to thermal gradient through the thickness during startup and shutdown. Therefore, the requirement to be satisfied and from which the allowable pressure for any assumed rate of temperature change can be determined is:
Figure G-2214-1M

\[ \Delta T_w = K_t/M_p \]
\[ \Delta T_w \text{ temperature difference through the wall } ^\circ C \]
\[ K_t \text{ stress intensity factor, MPa} \sqrt{m} \]

Curve for \( \alpha = 0.7 \times 10^{-8}, E = 201 \times 10^4 \text{ MPa}, \nu = 0.3 \)

Crack Depth = Wall Thickness/4

Crack Depth = Wall Thickness/8

\( M_t \) (MPa/\( ^\circ C \))

Wall Thickness, mm

\[ 2K_{fm} + K_t < K_{fc} \] (1)

throughout the life of the component at each temperature with \( K_{fm} \) from G-2214.1, \( K_t \) from G-2214.3, and \( K_{fc} \) from Fig. G-2210-1.

The allowable pressure at any temperature shall be determined as follows.

(a) For the startup condition,

(1) consider postulated defects in accordance with G-2120;
(2) perform calculations for thermal stress intensity factors due to the specified range of heat-up rates from G-2214.3;
(3) calculate the \( K_{fc} \) toughness for all vessel beltline materials from G-2212 using temperatures and \( RT_{NDT} \) values for the corresponding locations of interest; and
(4) calculate the pressure as a function of coolant inlet temperature for each material and location. The allowable pressure-temperature relationship is the minimum pressure at any temperature determined from

(-a) the calculated steady-state \( (K_r = 0) \) results for the \( \frac{1}{4} \)-thickness inside surface postulated defects using the equation

\[
P = \frac{K_{fc}}{2M_n} \left[ \frac{t}{R_i} \right]
\]

(-b) the calculated results from all vessel beltline materials for the heatup stress intensity factors using the corresponding \( \frac{1}{4} \)-thickness outside-surface postulated defects and the equation

\[
P = \frac{K_{fc} - K_{fl}}{2M_n} \left[ \frac{t}{R_i} \right]
\]

(b) For the cooldown condition,

(1) consider postulated defects in accordance with G-2120;
(2) perform calculations for thermal stress intensity factors due to the specified range of cooldown rates from G-2214.3;
(3) calculate the \( K_{fr} \) toughness for all vessel beltline materials from G-2212 using temperatures and \( RT_{NDT} \) values for the corresponding location of interest; and
(4) calculate the pressure as a function of coolant inlet temperature for each material and location using the equation.

\[
P = \frac{K_{fc} - K_{fr}}{2M_n} \left[ \frac{t}{R_i} \right]
\]

The allowable pressure-temperature relationship is the minimum pressure at any temperature, determined from all vessel beltline materials for the cooldown stress intensity factors using the corresponding \( \frac{1}{4} \)-thickness inside-surface postulated defects.

Those plants having low temperature overpressure protection (LTOP) systems can use the following load and temperature conditions to provide protection against failure during reactor start-up and shutdown operation due to low temperature overpressure events that have been classified as Service Level A or B events. LTOP systems shall be effective.
at coolant temperatures less than 200°F (95°C) or at coolant temperatures corresponding to a reactor vessel metal temperature less than $RT_{NDT} + 50°F$ (28°C), whichever is greater. LTOP systems shall limit the maximum pressure in the vessel to 100% of the pressure determined to satisfy Eq. (1).

(a) **G-2216 Risk-Informed Allowable Pressure**

The equations given in this paragraph provide an alternative risk-informed methodology to compute allowable pressure as a function of inlet temperature for reactor heat-up and cool-down at rates not to exceed 100°F/hr (56°C/hr). The allowable pressure is defined as

(U.S. Customary Units)

$$p = (33.2 + 20.734 \times \exp[0.02(T - RT_{NDT} - 110)] - K_t) \times t/R_t \times 1/M_m$$

where

- $p =$ pressure (ksi)
- $RT_{NDT} = RT_{NDT(u)} + \Delta RT_{NDT}$ and is the reference nil ductility temperature adjusted for irradiation effects at the maximum depth of the postulated quarter thickness flaw stipulated in G-2214.3, °F
- $RT_{NDT(u)} =$ equivalent to the unirradiated $RT_{NDT}$ calculated in accordance with NB-2300, °F
- $\Delta RT_{NDT} =$ an adjustment for irradiation effects, °F
- $T =$ temperature at the maximum depth of the postulated quarter thickness flaw stipulated in G-2214.3, °F

(SI Units)

$$p = (36.5 + 22.783 \times \exp[0.036(T - RT_{NDT} - 61)] - K_t) \times t/R_t \times 1/M_m$$

where

- $p =$ pressure, MPa
- $RT_{NDT} = RT_{NDT(u)} + \Delta RT_{NDT}$ and is the reference nil ductility temperature adjusted for radiation effects at the maximum depth of the postulated quarter thickness flaw stipulated in G-2214.3, °C
- $RT_{NDT(u)} =$ equivalent to the unirradiated $RT_{NDT}$ calculated in accordance with NB-2300, °C
- $\Delta RT_{NDT} =$ an adjustment for irradiation effects, °C
- $T =$ temperature at the maximum depth of the postulated quarter thickness flaw stipulated in G-2214.3, °C

$K_t$ is as stipulated in G-2214.3, and $t$, $R_t$, $M_m$ are as stipulated in G-2214.1. The evaluation is to be performed for all conditions, materials, and locations as described in G-2215.

The operational pressure-temperature limits are based on the temperature at the reactor coolant inlet temperature, which is assumed to equal the temperature at the vessel inner surface. Figure G-2214-1 or Fig. G-2214-1M and Fig. G-2214-2 can be used to determine the temperature at the vessel inner surface corresponding to the temperature at the maximum depth of the postulated quarter thickness flaw stipulated in G-2214.3.

$\Delta RT_{NDT}$ is determined from plant-specific surveillance data, or the irradiation degradation model used to compute the risk-informed allowable pressure as shown in Eq. (2) or other irradiation degradation models acceptable to the regulatory authority having jurisdiction at the plant site.

\[ \Delta RT_{NDT} = MF + CRP \]

(U.S. Customary Units)

$$MF = A(1 - 0.001718T)(1 + 6.13P Mn^{2.47})(\phi_0)^{1/2}$$

where

- $A = 1.140 \times 10^{-7}$ for forgings
- $1.561 \times 10^{-7}$ for plates
- $1.417 \times 10^{-7}$ for welds
\[ \Phi_e = \begin{cases} \Phi & \text{for } \Phi \geq 4.39 \times 10^{10} \\ \Phi \left( \frac{4.39 \times 10^{10}}{\Phi} \right)^{0.259} & \text{for } \Phi < 4.39 \times 10^{10} \end{cases} \]

\[ \Phi_e = \text{effective neutron fluence, cm}^{-2} \]
\[ \Phi = \text{neutron fluence, cm}^{-2} \]
\[ \phi = \text{neutron flux, cm}^{-2}\text{s}^{-1} \]

\[ CRP = B \left( 1 + 3.77N_i^{1.191} \right) f(Cu_e, P) g(Cu_e, Ni, \Phi_e) \]

where

\[ B = \begin{cases} 102.3 & \text{for forgings} \\ 135.2 & \text{for plates in vessels manufactured by Combustion Engineering (CE)} \\ 102.5 & \text{for non-CE plates} \\ 155.0 & \text{for welds} \end{cases} \]

\[ Ni = \text{bulk material nickel content, wt. \%} \]

\[ Cu_e = \begin{cases} 0 & \text{for } Cu < 0.072 \\ \min \left[ Cu, Cu_{\text{max}} \right] & \text{for } Cu > 0.072 \end{cases} \]

\[ Cu_e = \text{effective material copper content, wt. \%} \]

\[ Cu = \text{bulk material copper content, wt. \%} \]

\[ Cu_{\text{max}} = 0.243 \text{ for Linde 80 welds with } Ni > 0.5 \]

\[ = 0.301 \text{ for all other materials } \]

\[ f(Cu_e, P) = \begin{cases} 1 & \text{for } Cu \leq 0.072 \\ \left[ Cu_e - 0.072 \right]^{-0.668} & \text{for } Cu > 0.072 \text{ and } P \leq 0.008 \\ \left[ Cu - 0.072 + 1.359(P - 0.008) \right]^{0.668} & \text{for } Cu > 0.072 \text{ and } P > 0.008 \end{cases} \]

\[ g(Cu_e, Ni, \Phi_e) = \frac{1}{2} + \frac{1}{2} \tanh \left[ \log_{10}(\Phi_e) + 1.139Cu_e - 0.448Ni - 18.120 \right] \]

\[ MF = A \left( \frac{0.945 - 0.003092T_f}{1 + 6.13P Mn^{2.47}} \right) (\Phi_e)^{1/2} \]

where

\[ A = 6.333 \times 10^8 \text{ for forgings} \]
\[ = 8.672 \times 10^8 \text{ for plates} \]
\[ = 7.872 \times 10^8 \text{ for welds} \]

\[ T_f = \text{irradiation temperature, } ^\circ\text{C} \]

\[ P = \text{bulk material phosphorus content, wt. \%} \]

\[ Mn = \text{bulk material manganese content, wt. \%} \]
\[
\Phi_e = \begin{cases} 
\Phi for \phi \geq 4.39 \times 10^{10} \\
\left(4.39 \times 10^{10}\right)^{0.259} / \phi for \phi < 4.39 \times 10^{10}
\end{cases}
\]

\[CRP = B \left(1 + 3.77N_i^{0.191}\right) / f(Cu_e, P)g(Cu_e, N_i, \Phi_e)\]

where

- \( B = 56.83 \) for forgings
- 75.11 for plates in vessels manufactured by Combustion Engineering (CE)
- 56.94 for non-CE plates
- 86.11 for welds
- \( N_i = \) bulk material nickel content, wt. %

\[Cu_e = \begin{cases} 
0 for Cu < 0.072 \\
\text{minimum } [Cu, Cu_{\text{max}}] for Cu > 0.072
\end{cases}\]

\[Cu_e = \text{effective material copper content, wt. %}\]

\[Cu = \text{bulk material copper content, wt. %}\]

\[Cu_{\text{max}} = 0.243 \text{ for Linde 80 welds with } N_i > 0.5\]

\[= 0.301 \text{ for all other materials}\]

\[f(Cu_e, P) = \begin{cases} 
0 for Cu \leq 0.072 \\
\left(\frac{Cu_e - 0.072}{0.668}\right) for Cu > 0.072 and P \leq 0.008 \\
\left[\frac{Cu - 0.072 + 1.359(P - 0.008)}{0.668}\right] for Cu > 0.072 and P > 0.008
\end{cases}\]

\[g(Cu_e, Ni, \Phi_e) = \frac{1}{2} + \frac{1}{2} \tanh\left(\frac{1.139Cu_e}{0.448N_i - 18.120}\right)^{0.629}\]

- **G-2220** NOZZLES, FLANGES, AND SHELL REGIONS NEAR GEOMETRIC DISCONTINUITIES

**G-2221 General Requirements**

The same general procedure as was used for the shell and head regions in G-2210 may be used for areas where more complicated stress distributions occur, but certain modifications of the procedures for determining allowable applied loads shall be followed in order to meet special situations, as stipulated in G-2222 and G-2223.

(a) **G-2222 Consideration of Membrane and Bending Stresses**

(a) Equation G-2215(1) requires modification to include the bending stresses which may be important contributors to the calculated \( K_e \) value at a point near a flange or nozzle. The terms whose sum must be \(< K_{eb} \) for Level A and B conditions are:

1. \( 2K_{bm} \) from G-2214.1 for primary membrane stress;
2. \( 2K_{bb} \) from G-2214.2 for primary bending stress;
3. \( K_{bm} \) from G-2214.1 for secondary membrane stress;
4. \( K_{bb} \) from G-2214.2 for secondary bending stress.

(b) For purposes of this evaluation, stresses which result from bolt preloading shall be considered as primary.
(c) It is recommended that when the flange and adjacent shell region are stressed by the full intended bolt preload and by pressure not exceeding 20% of the preoperational system hydrostatic test pressure, minimum metal temperature in the stressed region should be at least the initial $RT_{NDT}$ temperature for the material in the stressed regions plus any effects of irradiation at the stressed regions.

(d) Thermal stresses shall be considered as secondary except as provided in NB-3213.13(b). The $K_t$ of G-2214.3(b) is recommended for the evaluation of thermal stress.

G-2223 Toughness Requirements for Nozzles

(a) A quantitative evaluation of the fracture toughness requirements for nozzles is not feasible at this time, but preliminary data indicate that the design defect size for nozzles, considering the combined effects of internal pressure, external loading and thermal stresses, may be a fraction of that postulated for the vessel shell. Nondestructive examination methods shall be sufficiently reliable and sensitive to detect these smaller defects.

(b) WRCB 175 provides an approximate method in Paragraph 5C(2) for analyzing the inside corner of a nozzle and cylindrical shell for elastic stresses due to internal pressure stress.

(c) Fracture toughness analysis to demonstrate protection against nonductile failure is not required for portions of nozzles and appurtenances having a thickness of 2.5 in. (63 mm) or less, provided the lowest service temperature is not lower than $RT_{NDT}$ plus 60°F (33°C).

G-2300 LEVEL C AND LEVEL D SERVICE LIMITS

G-2310 RECOMMENDATIONS

The possible combinations of loadings, defect sizes, and material properties which may be encountered during Levels C and D Service Limits are too diverse to allow the application of definitive rules, and it is recommended that each situation be studied on an individual case basis. The principles given in this Appendix may be applied, where applicable, with any postulated loadings, defect sizes, and material toughness which can be justified for the situation involved.

G-2400 HYDROSTATIC TEST TEMPERATURE

(a) For system and component hydrostatic tests performed prior to loading fuel in the reactor vessel, it is recommended that hydrostatic tests be performed at a temperature not lower than $RT_{NDT}$ plus 60°F (33°C). The 60°F (33°C) margin is intended to provide protection against nonductile failure at the test pressure.

(b) For system and component hydrostatic tests performed subsequent to loading fuel in the reactor vessel, the minimum test temperature should be determined by evaluating $K_t$. The terms given in (1) through (4) below should be summed in determining $K_t$:

1. $1.5K_{mm}$ from G-2214.1 for primary membrane stress;
2. $1.5K_{bb}$ from G-2214.2 for primary bending stress;
3. $K_{mm}$ from G-2214.1 for secondary membrane stress;
4. $K_{bb}$ from G-2214.2 for secondary bending stress.

$K_t$ calculated by summing the four values given in (1) through (4) above, shall not exceed the applicable $K_t$ value.

(c) The system hydrostatic test to satisfy (a) or (b) should be performed at a temperature not lower than the highest required temperature for any component in the system.

G-2500 RISK-INFORMED HYDROSTATIC LEAK TESTING

G-2510 HYDROSTATIC LEAK TEST TEMPERATURE

For heat-up and cool-down rates not to exceed 40°F/hr (22°C/hr), an alternative risk-informed leak test temperature, $T$, may be determined as the larger of

(U.S. Customary Units)

\[ T = RT_{NDT} + 60 + \ln[(K_{mm} + K_{fr} - 33.2)/20.734]/0.02 \]

for an outside surface flaw or

\[ T = RT_{NDT} + 60 + \ln[(K_{mm} - 33.2)/20.734]/0.02 \]