ARTICLE C-3000
FLAW GROWTH ANALYSIS

C-3100  SCOPE

This Article provides the methodology for determination of subcritical flaw growth during the evaluation period.

C-3200  SUBCRITICAL FLAW GROWTH ANALYSIS

If a flaw is characterized in terms of an equivalent axial and circumferential flaw, the maximum depth \( a_f \) and the maximum length \( \ell_f \) at the end of the evaluation period shall be determined by consideration of subcritical flaw growth. Flaw growth in austenitic piping can be due to cyclic fatigue loading, stress corrosion cracking (SCC) under sustained load, or a combination of both. Flaw growth in ferritic piping can be due to cyclic fatigue loading. SCC has not been observed to be a significant flaw growth mechanism in ferritic piping. Residual stress effects shall be included in the analytical evaluation of both growth mechanisms.

C-3210  FLAW GROWTH DUE TO FATIGUE

(a) Fatigue flaw growth due to cyclic loading in piping can be characterized by the following equation relating the rate of flaw growth, \( da/dN \), to the range of the applied stress intensity factor, \( \Delta K_f \):

\[
\frac{da}{dN} = C_o (\Delta K_f)^n
\]

(1)

where \( \Delta K_f \) is the range of the applied stress intensity factor and \( C_o \) and \( n \) are parameters dependent on material and environmental conditions. The flaw growth rate parameters are in C-8400. For subsurface flaws, surface flaw solutions may be used to calculate stress intensity factors, where the flaw depth, \( a \), in the procedures below shall be set equal to the total radial depth, \( 2a \).

(b) A cumulative fatigue flaw growth calculation shall be performed using the appropriate fatigue crack growth rates in C-8400 and the operating conditions and transients that apply during the evaluation period. \( \Delta K_f \) shall be determined for each transient using the bounding elliptical or semieliptical flaw model described in Article C-2000 and the methods for \( K_f \) determination in Article C-7000. Each transient should be considered in approximate chronological order as follows:

1. Determine \( \Delta K_f \), the maximum range of \( K_f \) fluctuations associated with the transient.
2. Determine the incremental flaw growth corresponding to \( \Delta K_f \) from the fatigue flaw growth rate equation.
3. Update the flaw dimensions \( a \) and \( \ell \).
4. Repeat these calculations for the next transient using the updated flaw dimensions.

(c) After all transients have been considered, this procedure yields the final flaw size \( a_f \) and \( \ell_f \) at the end of the evaluation period considering only fatigue flaw growth.

C-3220  FLAW GROWTH DUE TO STRESS CORROSION CRACKING

(a) Subcritical flaw growth due to SCC is a function of material condition, environment, stress intensity factor due to sustained loading, and 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 \( K_f \). Sustained loads resulting from pressure and steady state thermal stresses as well as residual stresses should be included. Appropriate experimental data on residual stress distribution for different pipe sizes and flaw growth rate as a function of sustained \( K_f \) should be used. The procedure used for determining the cumulative flaw growth is as follows.

1. Determine the sustained stress intensity factor \( K_f \) for a given steady-state stress condition.
(b) The correlation at upper-shelf temperatures for use with Charpy V-notch (CVN) data is

(U.S. Customary Units)

\[ J_{\text{im}} = 10 \text{CVN} \]

(SI Units)

\[ J_{\text{im}} = 1.3 \text{CVN} \]

and \( J_{\text{im}} \) shall replace \( J_{\text{lc}} \) when this Charpy correlation is used. In the absence of specific data, the upper-shelf temperatures 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, \( J_{\text{lc}} \), 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 \( K_{\text{lc}} \) 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 \( J_{\text{lc}} \) shall be determined from the following:

\[ J_{\text{lc}} = 1000 \left( \frac{K_{\text{lc}}}{E} \right)^{0.5} \]

Alternatively, values for \( J_{\text{lc}} \) 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 test.

C-8330 OTHER PIPING MATERIALS

For other piping materials, including nonferrous alloys and cast austenitic stainless steel not covered in this Appendix, similar procedures may be used to establish \( J_{\text{lc}} \), \( K_{\text{lc}} \), or \( K_e \). Material condition, testing parameters, test results, and toughness correlations shall be appropriate for the pipe material and flaw orientation under analytical 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 \( (K_{\text{min}}/K_{\text{max}}) \), and environment. Reference fatigue crack growth rates for air and water environments are given by the following:

\[ C_0 = CS (18) \]

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

(U.S. Customary Units)

\[ C = 10 \left[ -10.009 + 8.12 \times 10^{-4} T - 1.13 \times 10^{-6} T^2 + 1.02 \times 10^{-9} T^3 \right] \]
The fatigue crack growth behavior of austenitic stainless steel is affected by the $R$ ratio ($K_{\text{min}}/K_{\text{max}}$) and the environment. For air environments, and with reference to the material constant $C_0$ in eq. C-3210(a)(1) for the fatigue crack growth rate, $C_0 = 0$ for $\Delta K_I < \Delta K_{th}$ where $\Delta K_{th}$ is the threshold $\Delta K_I$ value below which the fatigue crack growth rate is negligible. $\Delta K_{th}$ is expressed by $K_{\text{max}} - K_{\text{min}}$, even when $R < 0$. $\Delta K_{th}$ in units of ksi\(\sqrt{\text{in.}}\) (MPa\(\sqrt{\text{m}}\)) is given by

(U.S. Customary Units)

For 70°F

$$\Delta K_{th} = 2.9(1 - 0.74R)$$

For 392°F and above

$$\Delta K_{th} = 4.7(1 - 0.46R)$$

(SI Units)

For 21°C

$$\Delta K_{th} = 3.2(1 - 0.74R)$$

For 200°C and above

$$\Delta K_{th} = 5.2(1 - 0.46R)$$

For intermediate temperatures between 70°F (21°C) and 392°F (200°C), linear interpolation is permissible.
Figure C-8410-1
Reference Fatigue Crack Growth Curves for Austenitic Stainless Steels in Air Environments

GENERAL NOTES:
(a) Solid lines for 70°F; dashed lines for 350°F.
(b) For other R ratios and temperatures, see C-8410.
Figure C-8410-1M
Reference Fatigue Crack Growth Curves for Austenitic Stainless Steels in Air Environments

GENERAL NOTES:
(a) Solid lines for 21°C; dashed lines for 200°C.
(b) For other R ratios and temperatures, see C-8410.

200°C
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Note to Editor: Insert this figure as the new Figure C-8410-1M