**ENGINEERING STANDARD**

**EN-CS-S-008-MULTI**  
rev. 0  
**Pipe Wall Thinning Structural Evaluation**

**Effective Date: 1-1-2010**

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Safety Related: X Yes

EC No(s).

Prepared by: Kai Lo  
Approved by: R. Drake

Date: 10/26/09

**Process Applicability Exclusion (EN-LI-100) / Programmatic Exclusion**

All Sites: [ ] Specific Sites: ANO [ ] GGNS [ ] IPEC [ ] JAF [ ] PLP [ ] PNPS [ ] RBS [ ] VY [ ] W3 [ ]
Requirements and Revision Summary

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1.0 PURPOSE

1.1 The purpose of this standard is to provide consistent methodology for performing structural evaluations of pipe wall thinning for ASME Section XI Class 1, 2, and 3, carbon and low alloy steel piping. This standard is also applicable for non-safety related piping using Attachment 7.6 of this procedure.

1.2 This standard can be used for, but not limited to, evaluation of internal or external thinning due to Flow Accelerated Corrosion (FAC), Microbiologically Induced Corrosion (MIC), and general erosion/corrosion. The methodology for evaluation of thinning due to MIC and general erosion/corrosion is the same as FAC; however, wall thinning rates are different and should be calculated as shown in Section 5.1.

1.3 This standard is applicable to Entergy Nuclear (EN) nuclear power plants for which the piping was designed in accordance with the ASME Section III, ANSI B31.7 and USAS/ANSI B31.1 code [2.1, 2.20, 2.21].

1.4 This standard is applicable to piping and fittings and can not be used to evaluate other components such as valves, pump casings, etc.

2.0 REFERENCES

2.1 USAS/ANSI B31.1, "Power Piping", (For applicable code year, see individual plant FSAR)
2.2 IP3 FSAR
2.3 JAF FSAR
2.4 ASME B & PV Code Case N-597, Rev. 2
2.5 PS-S-001 Rev.1, "Localized Pipe Wall Thinning and Crack Like Flaw Evaluation Standard"
2.6 ASME B & PV Code Case N-513-2
2.7 PVP-Volume 264, Piping, Supports, and Structural Dynamics, ASME 1993, P51-55
2.8 IP2 FSAR
2.9 PNPS FSAR
2.10 VY FSAR
2.11 ASME 2001 B & PV Code, Section XI, Appendix C
2.12 EN-DC-126, “Engineering Calculation Process"
2.13 USNRC Regulatory Guide 1.147
2.15 ENN-DC-185, “Through-Wall Leaks in ASME Section XI Class 3 Moderate Energy Piping Systems “
2.18 ASME B & PV Code Case N-661
2.19 Roark’s Formulas for Stress & Strain, W.C. Young, Sixth Edition
2.20 USAS B31.7, “Nuclear Power Piping”, (For applicable code year, see individual plant FSAR)
2.21 ASME Boiler and Pressure Vessel Code, Section III, (For applicable code year, see individual plant FSAR)

2.22 ANO-1 FSAR
2.23 ANO-2 FSAR
2.24 GGNS FSAR
2.25 WF3 FSAR
2.26 PLP FSAR
2.27 RBS FSAR
2.28 EN-DC-115, Engineering Change Process

3.0 DEFINITIONS
3.1 $A$ - Additional thickness per ANSI B31.1 code, (in)
3.2 $A_i$ - Predicted inside cross-section area with pipe wall thinning, $(\text{in}^2)$
3.3 $A_m$ - Predicted metal cross-section area with pipe wall thinning, $(\text{in}^2)$
3.4 $A_o$ - Total cross-section area of pipe based on outside diameter, $\pi D_o^2/4$, $(\text{in}^2)$
3.5 $D_o$ - Pipe outside diameter, (in)
3.6 $i$ - Stress Intensification Factor for nominal thickness (See Appendix D of Ref. 2.1)
3.7 $i'$ - Stress Intensification Factor based on average measured thinned thickness
3.8 ISI - In-Service Inspection. Piping components are classified as ISI Class 1, 2, and 3 in accordance with Regulatory Guide 1.26, 10CFR50.2V and/or the ISI Program Plan
3.9 $K_{Nor}$ - Allowable stress factor for Normal (or Design) Conditions. (See Attachment 7.5 for plant specific values)
3.10 $K_{Up}$ - Allowable stress factor for Upset Conditions. (See Attachment 7.5 for plant specific values)
3.11 $K_{Emg}$ - Allowable stress factor for Emergency Conditions. (See Attachment 7.5 for plant specific values)
3.12 $K_{Fau}$ - Allowable stress factor for Faulted Conditions. (See Attachment 7.5 for plant specific values)
3.13 $L$ - Maximum extent of a local thinned area with wall thickness less than $t_{nom}$, (in.), (see Figure A-1 of Attachment 7.6)
3.14 $L_m$ - Maximum extent of a local thinned area with wall thickness less than $t_{min}$, (in.), (see Figure A-1 of Attachment 7.6)
3.15 $L_{max(a)}$ - Maximum axial extent of a local thinned area with wall thickness less than $t_{min}$, (in.), (see Figure A-1 of Attachment 7.6)
3.16 $L_{max(a),max}$ - Maximum of the axial extent of two adjacent local thinned areas with wall thickness less than $t_{min}$, (in.), (see Figure A-3 of Attachment 7.6)
3.17 \( L_{\text{min}} \) - Maximum transverse extent of a local thinned area with wall thickness less than \( t_{\text{min}} \), (in.),
(see Figure A-1 of Attachment 7.6)

3.18 \( L_{\text{min,avg}} \) - Average of the extent of thickness less than \( t_{\text{min}} \) for two adjacent thinned areas, (in.),
(see Figure A-2 of Attachment 7.6)

3.19 ME - Moderate Energy; Piping system operating pressure \( \leq 275 \) psig and operating temperature \( \leq 200 \) °F

3.20 \( M_b \) - Resulting bending moment from the design analysis of record for each loading condition under consideration, (in-lb)

3.21 \( P \) - Design pressure, (psi)

3.22 \( P_e \) - Thermal expansion stress, (ksi)

3.23 \( P_m \) - Piping axial stress due to design pressure, (ksi)

3.24 \( P_b \) - Piping bending stress, (ksi)

3.25 \( R \) - Pipe mean radius, \( (D_0 - t_{\text{nom}})/2 \), (in)

3.26 \( R_b \) - Pipe elbow bend radius, (in)

3.27 \( R_{\text{nom}} \) - Mean radius of piping item based on the minimum wall thickness, (in)

3.28 \( R_{\text{nom}} \) - Pipe nominal radius, (in)

3.29 \( R_0 \) - Pipe outside radius, \( D_0 / 2 \), (in)

3.30 \( S \) - Piping axial stress = \( P_m + P_b \), (ksi)

3.31 \( S_{\text{th}} \) - Pipe thermal expansion allowable stress, (psi)

3.32 \( S_b \) - Pipe axial stress due to bending moments, (psi)

3.33 \( S_{\text{tor}} \) - Pipe axial stress at Normal Conditions or Stress Due to Sustained Loads [2.1], (psi)

3.34 \( S_{\text{ring}} \) - Pipe axial stress at Emergency Conditions or Stress Due to Occasional Loads [2.1], (psi)

3.35 \( S_{\text{fa}} \) - Pipe axial stress at Faulted Conditions, (psi)

3.36 \( S_{\text{a}} \) - Pipe allowable stress at operating temperature, (psi), [see Appendix A of Ref. 2.1],

3.37 \( S_{\text{th}} \) - Pipe thermal expansion stress or Additive Stress [2.1], (psi)

3.38 \( S_{\text{th,fa}} \) - Pipe thermal expansion stress for the thinned section, (psi)

3.39 \( S_{\text{a}} \) - Pipe axial stress due to pressure, (psi)

3.40 \( S_{\text{ups}} \) - Pipe axial stress at Upset Conditions or Stress Due to Occasional Loads [2.1], (psi)

3.41 \( SF \) - Safety Factor for Wear Rate, (1.1 is recommended per EN-DC-315)

3.42 \( t_{\text{meas}} \) - Minimum measured pipe wall thickness of the latest inspection, (in)

3.43 \( t_{\text{min}} \) - Minimum required pipe wall thickness for internal pressure, (in)

3.44 \( t_{\text{min,pipe}} \) - Minimum required pipe wall thickness for straight pipe, (in)

3.45 \( t_{\text{min,axial}} \) - Minimum required pipe wall thickness for axial stress, (in)

3.46 \( t_{\text{min}} \) - Minimum required pipe wall thickness required for hoop stress, axial stress and larger than \( \eta t_{\text{nom}} \), (in)
Calculate \( t \) shall be determined as provided in Attachment 7.7.

The \( \text{Wear rate} \) be obtained from the FAC engineer, applicable.

For related piping components, minimum wall thickness criteria that are not included in this standard can be used if it is justified by documented site specific evaluations.

### 4.0 Responsibilities

4.1 Manager of Design Engineering at each site is responsible for assuring the proper implementation of this standard.

4.2 Implementing Engineer is responsible for ensuring that calculations generated from this standard shall be performed in accordance with the EN calculation procedure, EN-DC-126.

4.3 Wear rates for inspections performed under EN-DC-315 is the responsibility of the FAC engineer.

4.4 Civil/Mechanical Engineering Section is responsible to perform structural evaluation for pipe wall thinning and flaws.

### 5.0 Details

The methods of pipe wall thinning evaluation in this standard are steps to assess the acceptability of the minimum predicted thickness, \( t_p \) (See Figure 1 for illustration). First an initial screening is performed using the \( t_p \) value to determine action to be taken. The actions are: Accept-as-Is, Evaluate, or Repair/Replace. If a structural evaluation is performed, it shall satisfy the pipe code stress requirements for both hoop and axial directions [2.4].

The approaches of the uniformly thinned section and the actual thinned section for the structural evaluation are both provided in this standard. The uniformly thinned section methodology illustrated in Figure 4 assumes a uniformly thinned section with the minimum measured thickness. This approach is simple but it may give overly conservative results when the pipe wall thinning is localized. Re-evaluation using the actual thinned section may be required to reduce the conservatism.

For non-safety related piping components, minimum wall thickness criteria that are not included in this standard can be used if it is justified by documented site specific evaluations.

### 5.1 Predicted Thickness at Next Inspection, \( t_p \)

The wear rate (\( W \)) shall be obtained from the FAC engineer, as applicable. Otherwise, it shall be determined as provided in Attachment 7.7.

Calculate \( t_p \):
\[ t_p = t_{\text{meas}} - S F W, \times Y \quad (1) \]

Wall thinning (wear) rates for phenomenon other than FAC may be difficult to predict and therefore should be determined on a case-by-case basis by the engineer.

5.2 Screening Rules

Determine actions for the acceptability of \( t_p \) by the screening criteria as follows:

<table>
<thead>
<tr>
<th>Screening Criteria</th>
<th>Actions</th>
</tr>
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<tbody>
<tr>
<td>( t_p \geq 0.875 \times t_{\text{nom}} \quad (2) )</td>
<td>Accept as is</td>
</tr>
<tr>
<td>( 0.875 \times t_{\text{nom}} &gt; t_p \geq 0.3 \times t_{\text{nom}} \text{ for Class 1} )</td>
<td></td>
</tr>
<tr>
<td>( \geq 0.2 \times t_{\text{nom}} \text{ for Class 2 &amp; 3} )</td>
<td>Evaluate</td>
</tr>
<tr>
<td>( 0.3 \times t_{\text{nom}} &gt; t_p \text{ for Class 1} )</td>
<td></td>
</tr>
<tr>
<td>( 0.2 \times t_{\text{nom}} &gt; t_p \text{ for Class 2 &amp; 3} )</td>
<td>Repair or replace (If piping meets the ANSI B31.1 code requirements, then immediate repair is not required. Repair or replace during the current operating cycle not to exceed the next refueling outage)</td>
</tr>
</tbody>
</table>

(For moderate energy Section XI Class 2 or 3 piping, perform ASME Code Case N-513-2 evaluation for through-wall flaws, if necessary)

Notes:

(1) The * is the multiplication sign herein.
(2) The rule is not applicable for the following cases:
   a. Class 1 short radius elbows, an evaluation shall be conducted to show that requirements of NB-3642.2 are met.
   b. Reinforcement area of tees or branch connections (see Figure 6), an evaluation of reinforcement area per ANSI B31.1 is shown in Attachment 7.4.
   c. Specific designed items as stated in Reference 2.4, Section 3500(a)(4).
5.3 Structural Evaluation

5.3.1 Hoop Stress Requirements

Minimum Wall Thickness, $t_{\text{min}}$:

$$t_{\text{min}} = \left( \frac{(P\times D_o)}{[2^*(S_h +0.4^*P)]} \right) + A$$

<table>
<thead>
<tr>
<th>Hoop Stress Requirements</th>
<th>Actions</th>
</tr>
</thead>
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<td>$t_p \geq t_{\text{min}}$</td>
<td>Accept for hoop stress</td>
</tr>
<tr>
<td>$t_p &lt; t_{\text{min}}$</td>
<td>Replace or repair</td>
</tr>
</tbody>
</table>

(A local thinning evaluation can be performed based on Code Case 597, however NRC approval is required for acceptance)

For Class 2/3 moderate energy pipe, ASME CCN-513-2 can be used without NRC approval.

Note: (3) a. For reducers (see Figure 3), $t_{\text{min}}$ shall be equal to $t_{\text{min}}$ of straight pipe connected to

the reducer end. For the conical portion of the reducer, $t_{\text{min}}$ shall be that of the larger diameter end.

b. For inner portion of elbows and pipe bends (see Figure 2), excluding a region within $1.5*(R_{\text{nom}}*t_{\text{nom}})^{0.5}$ of butt welds, $t_{\text{min}}$ shall be equal to

$$[0.5 + 0.5/(1 + (R_{\text{nom}}*R_p)*\cos\theta)]^{t_{\text{min}}-\text{pipe}}$$

c. For branch connections and tees, except at regions providing reinforcement of

the opening required by B31.1 Code, $t_{\text{min}}$ shall be as required for straight pipe.

Caution: When pressure is very low, $t_p$ may be unrealistically low.

5.3.2 Axial Stress Requirements

5.3.2.1 Uniformly Thinned Section Approach

Obtain axial stresses ($S_{\text{Nor}}, S_{\text{Up}}, S_{\text{Eng}}, S_{\text{Fau}}, S_{\text{Th}}$) and their allowable stresses [$\gamma K_{\text{Nor}} S_{\text{th}}, \gamma K_{\text{Up}} S_{\text{th}}, \gamma K_{\text{Eng}} S_{\text{th}}, \gamma K_{\text{Fau}} S_{\text{th}}, \gamma S_{\text{Th}}$] at the thinned area due to pressure and mechanical loads for Normal (or Design), Upset, Emergency, Faulted Conditions, and Thermal Expansion.

Determine the new stress intensification factor (SIF), $i$, if required, by using the average predicted wall thickness or conservatively using twice of the original SIF value around the thinning area of the component. The formulation of the stress intensification factors are listed in Appendix D of B31.1 Code [2.1].

Select the minimum thickness required for axial stress, $t_{\text{min}}^a$, to calculate the ratio of old and new section modulus:

$$Z/Z' = [D_o^4 - (D_o - 2t_{\text{nom}})^4]/[D_o^4 - (D_o - 2t_{\text{min}}^a)^4]$$

The new stresses due to pipe wall thinning shall satisfy the following
conditions:

Normal Conditions:
\[ \gamma^* K_{Nor} * S_n - [P*D_o/4t_{min} + (i'i)*(S_{Nor} - P*D_o/4t_{nom})*(Z/Z)] \geq 0 \quad \text{[Eq. 1]} \]

Upset Conditions:
\[ \gamma^* K_{Upr} * S_n - [P*D_o/4t_{min} + (i'i)*(S_{Ups} - P*D_o/4t_{nom})*(Z/Z)] \geq 0 \quad \text{[Eq. 2]} \]

Emergency Conditions:
\[ \gamma^* K_{Emg} * S_n - [P*D_o/4t_{min} + (i'i)*(S_{Emg} - P*D_o/4t_{nom})*(Z/Z)] \geq 0 \quad \text{[Eq. 3]} \]

Faulted Conditions: (if required)
\[ \gamma^* K_{Fau} * S_n - [P*D_o/4t_{min} + (i'i)*(S_{Fau} - P*D_o/4t_{nom})*(Z/Z)] \geq 0 \quad \text{[Eq. 4]} \]

Normal + Thermal Expansion:
\[ \gamma^* (S_n + S_t) - [P*D_o/4t_{min} + (i'i)*(S_{Nor} - P*D_o/4t_{nom} + S_{Thd})*(Z/Z)] \geq 0 \quad \text{[Eq. 5]} \]

The minimum of \( t_{min} \) can be obtained by the "Trial and Error Method" until one of the above four equations is close to zero.

It is noted that if \( t_p/t_{nom} \geq 0.75 \), and subject to no more than 150 equivalent full temperature cycles from the measurement date to the time of the next examination, then the thermal expansion stress need not to be considered.

<table>
<thead>
<tr>
<th>Axial Stress Requirements</th>
<th>Actions</th>
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<tbody>
<tr>
<td>( t_p \geq t_{min} )</td>
<td>Accept for axial stress</td>
</tr>
<tr>
<td>( t_p &lt; t_{min} )</td>
<td>Repair or replace, or calculate stresses based on actual thinned section in accordance with paragraph 5.3.2.2; For Class 2/3 moderate energy pipe, ASME CCN-513-2 can be used.</td>
</tr>
</tbody>
</table>

An example of the wall thinning evaluation with the uniform thinned section approach is shown in Attachment 7.1.

5.3.2.2 Actual Thinned Section Approach

5.3.2.2.1 Primary Piping Stress

A detailed stress analysis may be conducted based on the complete set of the wall thickness measurements around the circumferential direction of the actual thinned section of the pipe (See Figure 4). The nominal axial pressure stress, \( S_p \), shall be determined by:

\[ S_p = P \times A/A_n \]
The axial bending stress, $S_b$, for various loading conditions shall be determined by:

$$S_b = \frac{(M_b + P*A_b)}{Z_{min}}$$

The total axial stress, $S$, for various loading conditions shall satisfy their limits as follows:

$$S = S_0 + S_b \leq K*S_h$$

where $K = \gamma^*K_{Norm}, \gamma^*K_{Upset}, \gamma^*K_{Emergency}$, and $\gamma^*K_{Faulted}$ are for Normal (or Design), Upset, Emergency, and Faulted Conditions, respectively. The detailed methodology of this approach is described in Reference 2.4.

5.3.2.2.2 Thermal Expansion Stress

Determine the new thermal expansion stress as following:

$$S'_\text{The} = \gamma(Z_{norm}/Z_{min}) \times S_{\text{The}} \leq \gamma*S_A$$

An example of the detail calculation is shown in Attachment 7.2.

5.4 Potential Buckling of Thinned Region

When the ratio $R_o/t_o$ is greater than 50, the potential for buckling of the thinned region shall be evaluated. Following criteria is recommended to be used for evaluation of buckling.

**Local Buckling:** Buckling can only be caused by axial compressive stresses due to bending moments. Calculate local critical buckling stress as:

$$\text{Critical Buckling Stress} = 8.46*E*(t_{ave}/b)^{1.5}$$

(Note: This equation is based on Reference 2.19 Table 35 Case 1b, square plate with all edges clamped for a Poisson's ratio equal to 0.3)

where: $t_{ave}$ = average measured thickness in the flawed area
$b$ = length of flaw in the circumferential direction
$E$ = Modulus of Elasticity for pipe

**Overall Buckling:** Check piping overall buckling by methodology contained in ASME B & P V code Section III, NB/NC-3133.6 for cylinders under compression or any equivalent methodology.

5.5 Evaluation of Through-Wall Flaws

The through-wall flaw evaluation is applicable to only Class 2 or 3 moderate energy (ME) piping for through-wall flaws and flaws where $t_p$ is less than the required thickness for hoop and axial stress. The geometry of through-wall planar flaws is shown in Figure 5. The flaw evaluation is based on the requirements of ASME Code Case N-513 [2.6] with the following limitations:

1. Specific structural factors in paragraph 4.0 of reference 2.6 must be satisfied.
2. Code Case N-513-2 may not be applied to:
(a) Components other than pipe and tube.

(b) Leakage through a flanged joint.

(c) Threaded connections employing nonstructural seal welds for leakage prevention (through seal weld leakage is not a structural flaw; thread integrity must be maintained).

(d) Degraded socket welds.

3. Code Case N-513-2 may be applied to adjoining fittings and flanges to a maximum distance of \((R_{ot})^{0.5}\) from the weld centerline.

4. When the width of wall thinning \(W_m\) that exceeds \(t_m,\) is \(0.5(R_{ot})^{0.5}\) where \(W_m\) is defined in Fig. A-1 (partial through wall thinning), the flaw can be classified as a planar flaw, Attachment 7.3A or 7.3B can be used. If the above requirement is not satisfied, Attachment 7.6 can be used.

The acceptance is limited to the next scheduled outage. The detailed methodology of the evaluation is described in Reference 2.6. ASME Code Case N-513 also requires augmented examinations to determine extent of condition. These requirements are covered in ENN-DC-185 [2.15].

An example of a through-wall flaw evaluation is given in Attachment 7.3A and 7.3B.

5.6 Remaining Service Life (RSL) Estimation

The remaining service life of a thinned pipe shall be used to schedule the next inspection.

Calculate RSL:

\[
RSL = \frac{(t_{\text{meas}} - t'_{\text{min}})/(SF^*W_t)}
\]

Where \(t'_{\text{min}} = \text{Maximum of} (t_{\text{min}}, t_{\text{min}}^*, \beta_{t_{\text{min}}})\)

5.7 Restoration of Wall Thickness for Class 2 and 3 Carbon Steel Piping

If necessary, wall thickness restoration of Classes 2 and 3 carbon steel Raw Water Service piping can be performed in accordance with ASME Code Case N-661 [2.18] with the limitations of Regulatory Guide 1.147 [2.13].
Figure 1: Logic Diagram for Pipe Wall Thinning Evaluation
GENERAL NOTE:
Transition zones extend from the point on the ends where the diameter begins to change to the point on the central cone where the cone angle is constant.

Figure 2: Elbow and Nomenclature

Figure 3: Zone of Reducer
Figure 4: A Typical Thinned Pipe Cross-Section

Figure 5: Through-Wall Flaw Geometry

(a) Circumferential Flaw
(b) Axial Flaw
Required reinforcement = 1.07 \( f_{min} \) [cf. (2) - (3)]
Reinforcement areas = \( A_1, A_2, A_3, A_4, \) and \( A_5 \)

Excess wall in header

Example A

Excess wall in branch

Example B

Explaination of areas:

- Requirement reinforcement area
- Area \( A_1 \) = excess wall in header
- Area \( A_2 \) = excess wall in branch

\( \triangle \) Area \( A_3 \) = fill weld metal
\( \triangle \) Area \( A_4 \) = metal in ring, pad, or integral reinforcement [Note (21)]
\( \square \) Area \( A_5 \) = metal in saddle along run

Figure 6: Reinforcement of Branch Connections
[Per ANSI B31.1, Figure 104.3.1 (d)]
6.0 RECORDS

Use of this standard in conjunction with EN-DC-126 and EN-DC-115 process.

7.0 ATTACHMENTS

7.1 Example of Wall Thinning Evaluation Based on Uniformly Thinned Section
7.2 Example of Axial Stress Calculation With Actual Thinned Section
7.3A Example of ASME Code Case N-513 Evaluation for A Through-Wall Flaw for Carbon Steel
7.3B Example of ASME Code Case N-513 Evaluation for A Through-Wall Flaw for Austenitic steel
7.4 Example of Minimum Wall Evaluation at Reinforcement Area of Tee
7.5 Plant Specific Allowable Stress Factors
7.6 Recommendation for Safety Related Moderate Energy Class 2/3 and Non-Safety Related Piping
7.7 Recommended Guidance and Methods for Calculation of Wear Rates
7.8 Guide for using PS-S-001 as Informational Attachment
7.9 Informational Attachment
1. Design Parameters

- **D_0**: Outside Diameter, (in)
- **t_n**: Nominal Thickness, (in)
- **P**: Design Pressure, (psi)
- **T**: Design Temperature, (°F)
- **S_n**: Allowable Stress at Design Temperature, (psi) (See App. A of B31.1)
- **S_A**: Thermal Expansion Allowable Stress, (psi)
- **A**: Additional thickness per Section 104.1 of B31.1, (in)

<table>
<thead>
<tr>
<th>Material</th>
<th>P</th>
<th>T</th>
<th>S_n</th>
<th>S_A</th>
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<tr>
<td>A106 GB, SML</td>
<td>325</td>
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<td>15000</td>
<td>22500</td>
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</table>

2. Prediction of Min. Thickness at Next Inspection, t_p

\[ t_{\text{meas}} = \text{Wear Rate} \times (\text{in/yr}) \]
\[ t_m = t_{\text{meas}} \times S_F \times W \times Y \]
\[ R_{A/P} = \frac{R_{A/P}}{A/P} \]

3. Screening Rules for Pipe Wall Thinning

- **Rule 1**: Acceptance Standard = 0.875t_n
- **Rule 2**: Minimum Required Thickness
  - 0.3t_n for Class 1
  - 0.2t_n for Class 2 or 3
- **Rule 3**: Between the above two limits, wall thinning can be accepted by a structural evaluation

Action required based on the above screening rules for the inspected thinned pipe

- Class 1 piping
- Class 2 or 3 piping

4. Structural Evaluation

a. Minimum Thickness for Hoop Stress:

\[ t_{\text{min}} = \frac{P}{D_0} \left[ 2(S_n + 0.4P) \right] + A \] (in)

b. Minimum Thickness for Axial Stress:

- Is the thermal expansion stress required to be evaluated? Yes

<table>
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<tr>
<th>K_{APEC}</th>
<th>K_{AEP}</th>
<th>K_{EPEC}</th>
<th>K_{EPE}</th>
<th>γ</th>
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</table>
Original Piping Stresses

\[ S_{\text{Nor}} : \text{Normal Condition Stress, (psi)} \]

\[ S_{\text{Upst}} : \text{Upset Condition Stress, (psi)} \]

\[ S_{\text{Eng}} : \text{Emergency Condition Stress, (psi)} \]

\[ S_{\text{Ther}} : \text{Thermal Expansion Stress, (psi)} \]

\[ S_{\text{Max}} : \text{Maximum Stress, (psi)} \]

\[ S_{\text{Min}} : \text{Minimum Stress, (psi)} \]

\[ S_{\text{Nom}} : \text{Nominal Stress, (psi)} \]

\[ S_{\text{Min}} : \text{Minimum Stress, (psi)} \]

\[ S_{\text{Ther}} : \text{Thermal Expansion Stress, (psi)} \]

\[ S_{\text{Eng}} : \text{Emergency Condition Stress, (psi)} \]

Let \( t_{\text{nw}} = \)

\[ i = \]

\[ i' = \]

\[ \frac{i'}{i} = \]

\[ \frac{Z}{Z'} = [D_0^4 \cdot (D_0^2 \cdot 2t_{\text{nw}})^4]/[D_0^4 \cdot (D_0^2 \cdot 2t_{\text{nw}})^4] \]

Allowable Stress - Axial Stress \( \geq 0 \)

Normal conditions:

\[ \gamma'K_{\text{Nor}} S_{\text{Min}} \cdot [P*D_0/4t_{\text{nw}} + (i/i')(S_{\text{Nor}} - P*D_0/4t_{\text{nw}})*(Z/Z')] \geq 0 \]

Upset conditions:

\[ \gamma'K_{\text{Upst}} S_{\text{Min}} \cdot [P*D_0/4t_{\text{nw}} + (i/i')(S_{\text{Nor}} - P*D_0/4t_{\text{nw}})*(Z/Z')] \geq 0 \]

Emergency conditions:

\[ \gamma'K_{\text{Eng}} S_{\text{Min}} \cdot [P*D_0/4t_{\text{nw}} + (i/i')(S_{\text{Nor}} - P*D_0/4t_{\text{nw}})*(Z/Z')] \geq 0 \]

Normal and Ther. Expansion conditions:

\[ \gamma'N_{\text{Ther}} S_{\text{Min}} \cdot [P*D_0/4t_{\text{nw}} + (i/i')(S_{\text{Nor}} - P*D_0/4t_{\text{nw}})*(Z/Z')] \geq 0 \]

c. Minimum Required Thickness

Class 1: \( t_{\text{min}} = \text{Max.} \left[ t_{\text{min}}, 0.3t_{\text{min}} \right], \) (in); Acceptable if \( t_{\text{p}} \geq t_{\text{min}} \)

Class 2 & 3: \( t_{\text{min}} = \text{Max.} \left[ t_{\text{min}}, 0.2t_{\text{min}} \right], \) (in); Acceptable if \( t_{\text{p}} \geq t_{\text{min}} \)

5. Remaining Service Life (RSL)

Class 1: \( \text{RSL} = \left[ t_{\text{max}} - t_{\text{min}} \right]/(S^F W_i), \) (yr)

Class 2 & 3: \( \text{RSL} = \left[ t_{\text{max}} - t_{\text{min}} \right]/(S^F W_i), \) (yr)

Notes:

(1) The wear rate will be obtained from Responsible FAC Engineer or based on the Attachment 7.7.

(2) The acceptance standard \((0.875t_{\text{nw}})\) can not be applied to:

   1. Class 1 short radius elbows,
   2. Reinforcement area of a tee or branch connection, and
   3. For regions of piping designed to specific wall thickness requirements, such as counterbores or weld attachments.

(3) For the small end of reducers, the standard shall be based on the \( t_{\text{nw}} \) of the pipe size at the small end. For the large end, the large end transition and the conical portion, it shall be based on the \( t_{\text{nw}} \) of the pipe size at the larger end.

(4) The formula is applicable for straight pipes, bends, and elbows.

   For reducers, \( t_{\text{nw}} \) at each end shall be equal to \( t_{\text{min}} \) of straight pipe of the same nominal size as the reducer end.

   For the conical portion and transition at larger end of reducers, \( t_{\text{nw}} \) shall be that of the large diameter pipe end.

   For branch connections and tees, the reinforcement area of the opening shall be based on the B31.1 code.

(5) \( t_{\text{nw}} \) can be obtained by the "Trial and Error" method until the "Allowable Stress - Axial Stress" due to Normal, Upset, Emergency, and combined Normal and Thermal Expansion conditions are all positive and one of them shall be close to zero.

(6) \( i' \) can be calculated from Appendix D of ANSI B31.1. \( i' \) needs to be adjusted for the pipe wall thinning.

It is suggested that the average thickness or 2 times of the original value be used for the \( i' \) calculation.
### Attachment 7.2: Example of Axial Stress Calculation With Actual Thinned Section

Sheet 1 of 2

(Boxed values are input.)

<table>
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<th>( \theta_{in} )</th>
<th>( \theta_{an} )</th>
<th>( R_n )</th>
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</table>

Where:
- \( n \) : Identification of measurement grid around circumference.
- \( \theta_{in} \) : Min. thickness measured in nth grid.
- \( \theta_{an} \) : Min. predicted thickness of nth grid at next inspection. \( \theta_{in} ^\prime = \theta_{in} + \frac{\pi}{N} \cdot \Delta \theta / 2 \). \( \theta_{an} ^\prime = \theta_{in} + \frac{\pi}{N} \cdot \Delta \theta / 2 \).
- \( R_n \) : Inside thinned radius \( R_n = R - \theta_{in} \cdot \theta_{th} / 2 \).
- \( \theta_{th} \) : Circumferential angle clockwise of nth grid from vertical axis of pipe section.
- \( A_{0n} \) : \( R_n^2 \cdot R_{in}^2 \cdot \sin(\theta_{in}) \cdot (\pi / 2) \).
- \( B_{31} \) : \( R_n^3 \cdot \cos(\theta_{in}) \cdot (\pi / 2) \).
- \( B_{33} \) : \( R_n^3 \cdot \sin(\theta_{in}) \cdot (\pi / 2) \).
- \( I_{in} \) : \( R_n^4 \cdot R_{in}^4 \cdot \sin(\theta_{in}) \cdot (\pi / 2) \).
- \( I_{0n} \) : \( R_n^4 \cdot R_{in}^4 \cdot \sin(\theta_{in}) \cdot (\pi / 2) \).
- \( m \) : Total no. of thickness measurements (equal grid) in circumferential direction.

The origin of \( x-y \) coordinates is at the center of pipe section.
### Example of Axial Stress Calculation With Actual Thinned Section

#### SHEET 2 OF 2

**Gravity center of pressure area:** \( Y_p = \frac{B_p}{A_p} \), \( X_p = \frac{B_p}{A_p} \) (in)

**Gravity center of metal area:** \( X_m = \frac{A_m}{A_m} \), \( Y_m = \frac{A_m}{A_m} \) (in)

**Moment inertias at C.G. of metal area:** \( I_{x,y} = \int (x-x_m)^2 + (y-y_m)^2 \) \( dA \)

**Actual thinned section:**

\[ I_{thin} = \frac{(l_1 + l_2 - (l_1 - l_2)^2 + 4(l_1 l_2)^2)}{2}, \quad R_{max} = R_{thin} + (X_m + Y_m) \]

**Nominal section:**

\[ I_{nom} = \frac{0.375}{in^3} \]

**Uniformly thinned section:**

\[ I, R, Z \] (for \( I_{thin} = 0.115 \) in); \( (in^3, in, in^2) \)

---

### 2. Axial Stress for Actual Thinned Section

- **Design pressure:** \( P \) (psi)
- **Nominal section stress:** \( S_p = \frac{P A_{nom}}{1000} \)

**Stress Intensification for nominal thickness:** \( 0.75 \)

**Thermal stress range:** \( S_{th} = 0.75 S_p \)

**Operating Condition**

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<thead>
<tr>
<th>( S )</th>
<th>Normal</th>
<th>Upset</th>
<th>Emerg</th>
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<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>7.0</td>
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<tr>
<td>10.0</td>
<td>1.0</td>
<td>1.0</td>
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</table>

**Total bending moment for thinned section:** \( M = M_r + M_t \)

- **Thermal loadings:** \( M_r \)
- **Total bending moment:** \( M_t \)

**Allowable stress:** \( S_{allow} \)

- **Acceptable if:** \( S_{allow} \geq S' \)

**Cyclic Operation**

- **Thermal stress range:** \( S_{th} \)
- **Thermal allowable stress:** \( S_{allow} = (0.75) S_{th} \)

**Notes:**

1. It is recommended at least 18 measured wall thickness points around the circumference.
2. \( \gamma = 1.143 \) is used.
ATTACHMENT 7.3A  EXAMPLE OF ASME CODE CASE N-513 EVALUATION FOR A THROUGH-WALL FLAW FOR CARBON STEEL

Sheet 1 of 2

A. Pipe Parameters

- \( D_o \) = Pipe OD (in)
- \( t \) = Pipe wall thickness at flaw location (in)
- \( t_{aw} \) = average wall thickness of pipe circumference based on UT report (in)
- \( t_{nom} \) = nominal pipe wall thickness (in)
- \( p_d \) = Design Pressure (psi)
- \( p_o \) = Operational Pressure (psi)
- \( T \) = Metal Temperature at evaluation (°F)
- \( E \) = elastic modulus at \( T \) (ksi)
- \( v \) = poision ratio
- \( J_t \) = material toughness (lb/in)
- \( S \) = allowable stress for pipe (ksi)
- \( \sigma \) = stress intensification factor used in the stress analysis

Pipe Parameters Table

<table>
<thead>
<tr>
<th>Service Level</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
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<td>3.18</td>
</tr>
</tbody>
</table>

Service Level

- \( p_d D_o / (4 t_{aw}) \) or from stress summary: Axial stress due to design pressure (ksi)
- \( s = p_d D_o / (4 t_{aw}) + (0.75) t_{nom} \) Piping Axial Stress (ksi, from stress output)
- \( SF_a = \) Level A = 2.7; Level B = 2.4; Level c = 1.8; Level D = 1.3
- \( SF_b = \) Level A = 2.3; Level B = 2.0; Level c = 1.6; Level D = 1.4
- \( R_m = \) pipe mean radius (in) = \((D_o - t)/2\)
- \( E' = E / (1 - v^2) \)
- \( K_m = \) material critical stress intensity factor = \( J_{m0} (E/1000)^{0.5} \) (ksi/in)^{0.5}

B. Evaluate as a planar flaw in axial direction

Service Level

- \( c \times t = \) Half axial flaw length (in)
- \( p = \) pressure for the service level condition
- \( \rho_h = p \times D_o / (2t)/1000 \) (ksi)

For through wall flaw, \( a = c \):

- \( \lambda = c / (R_m)^{0.5} \)
- \( F = 1 + A \lambda + B \lambda^2 + C \lambda^3 + D \lambda^4 + E \lambda^5 \)

Where

- \( A = 0.0724 \)
- \( B = 0.6486 \)
- \( C = 0.2327 \)
- \( D = 0.0382 \)
- \( E = 0.0023 \)

\( K_n - K_0 - K_m = (SF_a) / (F_0 (2D))^{0.5} \) (ksi/in)^{0.5}

flaw length "2c"

Allowable Axial Flaw Length = Smaller "2c" of four service levels (in.) =

(Based on LEFM C-7400 & N513-2, I-3.0)
C. Evaluate as a planar flaw in circumferential direction

\[
\sigma_c = \left(9 \cdot p \cdot D_0 / (4t_{\text{nom}}) \right) / (0.75) \quad \text{(ksi)}
\]
\[
\sigma_p = \left(\sigma_c^2 \cdot (D_0 - 2t_{\text{nom}}) / (D_0 - 2t_{\text{nom}}) \right) \quad \text{(ksi)}
\]
\[
p = \text{pressure at the service level}
\]
\[
\sigma_a = pD_0 / (4t_{\text{nom}}): \text{Axial stress due to service pressure (ksi)}
\]
\[
K_{\text{c}} = \text{Flow area of hole}
\]

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<tr>
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<td>p=pressure at the service level</td>
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<td>0.030</td>
<td>0.034</td>
<td>0.041</td>
</tr>
<tr>
<td>α=α(τfN)</td>
<td>66.2</td>
<td>66.2</td>
<td>66.2</td>
<td>66.2</td>
</tr>
</tbody>
</table>

\[
r = r_{\text{nom}}/t
\]

<table>
<thead>
<tr>
<th>(r)</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A_{\text{al}}) = (A_{\text{al}}) + (A_{\text{al}})r + (A_{\text{al}})r² + (A_{\text{al}})r³</td>
<td>2.0292</td>
<td>1.6775</td>
<td>-0.0799</td>
<td>0.0018</td>
</tr>
<tr>
<td>(B_{\text{al}}) = (B_{\text{al}}) + (B_{\text{al}})r + (B_{\text{al}})r² + (B_{\text{al}})r³</td>
<td>7.9599</td>
<td>-4.4239</td>
<td>0.2104</td>
<td>-0.0046</td>
</tr>
<tr>
<td>(C_{\text{al}}) = (C_{\text{al}}) + (C_{\text{al}})r + (C_{\text{al}})r² + (C_{\text{al}})r³</td>
<td>7.7966</td>
<td>5.1668</td>
<td>0.0054</td>
<td>840.8</td>
</tr>
<tr>
<td>(A_{\text{al}}) = (A_{\text{al}}) + (A_{\text{al}})r + (A_{\text{al}})r² + (A_{\text{al}})r³</td>
<td>-3.2654</td>
<td>1.5278</td>
<td>-0.0727</td>
<td>0.0016</td>
</tr>
<tr>
<td>(B_{\text{al}}) = (B_{\text{al}}) + (B_{\text{al}})r + (B_{\text{al}})r² + (B_{\text{al}})r³</td>
<td>11.393</td>
<td>-3.9141</td>
<td>0.1862</td>
<td>-0.0041</td>
</tr>
<tr>
<td>(C_{\text{al}}) = (C_{\text{al}}) + (C_{\text{al}})r + (C_{\text{al}})r² + (C_{\text{al}})r³</td>
<td>-3.186</td>
<td>3.8476</td>
<td>-0.1830</td>
<td>0.0040</td>
</tr>
</tbody>
</table>

\[
F_{\text{an}} = 1 + A_{\text{al}}^2 + B_{\text{al}}^2 + C_{\text{al}}^2 + d_{\text{al}}^2 + e_{\text{al}}^2 + f_{\text{al}}^2
\]

\[
F_{\text{ap}} = 1 + A_{\text{al}}^2 + B_{\text{al}}^2 + C_{\text{al}}^2 + d_{\text{al}}^2 + e_{\text{al}}^2 + f_{\text{al}}^2
\]

\[
K_{\text{c}} - K_{\text{c}} = (C_{\text{al}} - C_{\text{al}}) \frac{1}{1 + C_{\text{al}}^2} \geq 0.0
\]

<table>
<thead>
<tr>
<th>Flaw length (2c)</th>
<th>0.002</th>
<th>0.003</th>
<th>0.004</th>
<th>0.005</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.88</td>
<td>2.55</td>
<td>2.55</td>
<td>2.55</td>
<td>2.55</td>
</tr>
</tbody>
</table>

\[
\text{Allowable Circumferential Crack Length} = \text{Smaller} "2c" \text{ of 4 service levels (in.)} = 1.88
\]

D. Check the hole penetration flow area

\[
t_{\text{nom}} = pD_0 / (2(1 + 0.4p)) \quad \text{(inch)}
\]
\[
l_{\text{nom}} = \text{length of through wall crack for the hole penetration in the axial direction of the pipe (inch)}
\]
\[
l_{\text{nom}} = \text{length of through wall crack for the hole penetration in the circumferential direction of the pipe (inch)}
\]
\[
A_r = \text{flow area of pipe (in²)}
\]
\[
A_r = \text{flow area per CN N-513-2 (in²)}
\]
\[
A_r = \text{allowable flow area} = \text{smaller of } A_r \text{ and } A_c
\]
\[
A_r = \text{flow area of hole} = L_{\text{nom}} L_{\text{nom}}
\]

\[
A_r = A_c
\]

| Yes |
ATTACHMENT 7.3B  EXAMPLE OF ASME CODE CASE N-513 EVALUATION FOR A THROUGH-WALL FLAW FOR AUSTENITIC STEEL

Sh. 1 of 2

A. Pipe Parameters

- \( D_0 \) = Pipe OD (in)
- \( t \) = Pipe wall thickness at flaw location (in)
- \( t_{ave} \) = average wall thickness of pipe circumferential based on UT report (in)
- \( t_{nom} \) = nominal pipe wall thickness (in)
- \( p_D \) = Design Pressure (psi)
- \( p_0 \) = Operational Pressure (psi) (< 275 psig)
- \( T \) = Metal Temperature at evaluation (°F) (< 200°F)
- \( E \) = elastic modulus at \( T \) (ksi)
- \( v \) = poison ratio
- \( J_{1c} \) = material toughness (lb/in)
- \( S_y \) = Material yield stress at \( T \) (ksi)
- \( S_u \) = Material ultimate tensile strength at \( T \) (ksi)
- \( i \) = SIF = stress intensification factor

<table>
<thead>
<tr>
<th>Service Level</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>pD ( / (4t_{nom}) ) or from UE&amp;C stress summary: Axial stress due to design pressure (ksi)</td>
<td>2.00</td>
<td>2.00</td>
<td>2.00</td>
<td>2.00</td>
</tr>
<tr>
<td>( s = p_D / (4t_{nom}) + (0.75)i_n ) Piping Axial Stress (ksi, from stress output)</td>
<td>3.68</td>
<td>7.06</td>
<td>7.82</td>
<td>7.82</td>
</tr>
</tbody>
</table>

- SF_a : Level A = 2.7; Level B = 2.4; Level c = 1.8; Level D = 1 [C-2621 & 2622]
- SF_b : Level A = 2.3; Level B = 2.0; Level c = 1.6; Level D = 1 [C-2621]
- \( \alpha \) = depth of flaw to wall thickness ratio (for through wall flaw, \( \alpha/t = 1.0 \))
- \( R_m = \) pipe mean radius (in) = \( (D_0 - t) / 2 \)
- \( E' = E(1 - v^2) \)
- \( K_{1c} \) = material critical stress intensity factor \( = J_{1c} / (1000)^{0.5} \) (ksi(in)^{0.5})

B. Evaluate as a planar flaw in axial direction [Based on ASME CC N513-2 3b, eqn 1, 2 & 3]

<table>
<thead>
<tr>
<th>Service Level</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>p = pressure at service level</td>
<td>90</td>
<td>150</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>( \sigma_n = pD / (2t) ) (psi)</td>
<td>6000</td>
<td>10000</td>
<td>10000</td>
<td>10000</td>
</tr>
<tr>
<td>( \sigma_i = (S_y + S_u) / 2 ) (psi)</td>
<td>47500</td>
<td>47500</td>
<td>47500</td>
<td>47500</td>
</tr>
<tr>
<td>( l_{ax} = ) allow through wall axial flaw (inch) = ( 1.58(R_m)^{0.25} \left[ \left( \sigma_n / (S_f S_w) \right)^{0.2} - 1 \right]^{0.5} )</td>
<td>5.3</td>
<td>3.3</td>
<td>4.7</td>
<td>6.8</td>
</tr>
</tbody>
</table>

Allowable Axial Flaw Length = \( l_{ax} \) of four service levels (in.) = 3.3
C. Evaluate as a planar flaw in circumferential direction

Service Level

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>

\[ \sigma''_c = \left( \frac{s + p_{\text{D}, \text{in}}}{(4t_{\text{nom}})} \right)^2 \]

\[ \sigma''_b = \sigma''_c \left( \frac{D_b - 2t_{\text{on}}} {D_b} \right)^2 \]

\[ p = \text{pressure at the service level (psi)} \]

\[ \sigma''_{m} = p \left( \frac{D_b}{(4t_{\text{nom}})} \right) \text{ Axial stress due to internal pressure (ksi)} \]

\[ c = \text{half crack length, trial & error until o.k. appears for both primary bending and membrane stress} \]

\[ \theta = \frac{c}{R_{\text{m}}} \text{ (radian)} \]

\[ \text{Chalf crack length, trial until a cap appears for both primary bend and membrane stress} \]

\[ \frac{s + p_{\text{D}, \text{in}}}{(4t_{\text{nom}})} \]

\[ \frac{s + p_{\text{D}, \text{in}}}{(4t_{\text{nom}})} \]

\[ (\theta + \beta) \leq \pi \]

\[ \beta = \frac{0.5(\pi + \beta + \theta)}{2} \]

\[ \sigma''_{b} = \frac{2\pi}{\pi} \left( \frac{\pi}{2} \right) \text{ psi} \]

\[ \sigma''_{m} = \frac{2\pi}{\pi} \left( \frac{\pi}{2} \right) \text{ psi} \]

\[ \text{Use } \sigma''_{b} \]

Check primary bending stress

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
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</thead>
<tbody>
<tr>
<td>47500</td>
<td>47500</td>
<td>47500</td>
<td>47500</td>
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<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.592</td>
<td>1.179</td>
<td>1.259</td>
<td>1.360</td>
</tr>
</tbody>
</table>

\[ \sigma''_{c} = \frac{(S_{c} + S_{b})}{2} \text{ (psi)} \]

\[ \text{If } (\theta + \beta) \leq \pi \text{ then flaws not penetrating the compressive side of pipe} \]

\[ \beta = \frac{0.5(\pi + \beta + \theta)}{2} \text{ psi} \]

\[ \sigma''_{b} = \frac{2\pi}{\pi} \left( \frac{\pi}{2} \right) \text{ psi} \]

\[ \sigma''_{m} = \frac{2\pi}{\pi} \left( \frac{\pi}{2} \right) \text{ psi} \]

Use \[ \sigma''_{b} \]

Check primary membrane stress

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>9175</td>
<td>18388</td>
<td>15945</td>
<td>13053</td>
</tr>
</tbody>
</table>

<table>
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<tbody>
<tr>
<td>16760</td>
<td>27817</td>
<td>27817</td>
<td>27817</td>
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<td>2656</td>
<td>7444</td>
<td>8633</td>
<td>8631</td>
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<table>
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<th>A</th>
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<th>D</th>
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</thead>
<tbody>
<tr>
<td>93</td>
<td>2</td>
<td>88</td>
<td>67</td>
</tr>
</tbody>
</table>

O.K. O.K. O.K. O.K.

Check two service levels

<table>
<thead>
<tr>
<th>A</th>
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<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>52</td>
<td>0.48</td>
<td>0.50</td>
<td>0.51</td>
</tr>
</tbody>
</table>

<table>
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<th>D</th>
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</thead>
<tbody>
<tr>
<td>7601</td>
<td>15151</td>
<td>13457</td>
<td>11485</td>
</tr>
</tbody>
</table>

<table>
<thead>
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<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>2815</td>
<td>6313</td>
<td>7476</td>
<td>8835</td>
</tr>
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<table>
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<th>C</th>
<th>D</th>
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</thead>
<tbody>
<tr>
<td>1015</td>
<td>3313</td>
<td>4476</td>
<td>5835</td>
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</table>

O.K. O.K. O.K. O.K.

<table>
<thead>
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<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>31.6</td>
<td>23.4</td>
<td>25.0</td>
<td>27.0</td>
</tr>
</tbody>
</table>

\[ \text{Flaw length } (2c^2) = 23.4 \]

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>23.4</td>
<td>25.0</td>
<td>27.0</td>
<td>23.4</td>
</tr>
</tbody>
</table>

F. Check the hole penetration flow area

<table>
<thead>
<tr>
<th>A</th>
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<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.100</td>
<td>0.100</td>
<td>0.100</td>
<td>0.100</td>
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</tbody>
</table>

<table>
<thead>
<tr>
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<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
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<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
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<th>C</th>
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</tr>
</thead>
<tbody>
<tr>
<td>291</td>
<td>291</td>
<td>291</td>
<td>291</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.72</td>
<td>0.72</td>
<td>0.72</td>
<td>0.72</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.87</td>
<td>0.87</td>
<td>0.87</td>
<td>0.87</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>932</td>
<td>932</td>
<td>932</td>
<td>932</td>
</tr>
</tbody>
</table>
1. Branch Connection Dimensions  
(See Figure 6 for nomenclature and dimensions) 

<table>
<thead>
<tr>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>α</td>
<td>Angle between axes of run and branch, (Deg.)</td>
</tr>
<tr>
<td>d</td>
<td>ID of branch, (in)</td>
</tr>
<tr>
<td>d₀</td>
<td>OD of branch, (in)</td>
</tr>
<tr>
<td>t₀</td>
<td>Min. predicted branch wall thickness, (in)</td>
</tr>
<tr>
<td>tᵣ₀</td>
<td>Min. required branch wall thickness, (in)</td>
</tr>
<tr>
<td>Dᵣ</td>
<td>OD of run, (in)</td>
</tr>
<tr>
<td>T₀</td>
<td>Min. predicted run wall thickness, (in)</td>
</tr>
<tr>
<td>Tᵣ</td>
<td>Min. required run wall thickness, (in)</td>
</tr>
</tbody>
</table>

2. Reinforcement Area Dimensions

<table>
<thead>
<tr>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>d₁</td>
<td>d/2sin(α), (in)</td>
</tr>
<tr>
<td>d₂</td>
<td>&quot;Half width&quot; of reinforcing zone = Max(d₁, 2T₀+Tᵣ+4t₀/2) but not more d₀, (in)</td>
</tr>
<tr>
<td>L</td>
<td>Altitude of reinforcement zone outside of run = 2.5t₀, (in)</td>
</tr>
<tr>
<td>tᵣ</td>
<td>Thickness of reinforcement ring, pad or saddle, (in)</td>
</tr>
<tr>
<td>Dᵣ</td>
<td>OD of reinforcement ring, pad or saddle (Effective only up to 2*d₂), (in)</td>
</tr>
</tbody>
</table>

3. Reinforcement Area Required for Pressure

\[ A_{req} = 1.07 \times tᵣ₀ \times d₀ \times [2 - \sin(\alpha)] \]  
\[ (in^2) \]

4. Reinforcement Area Provided

\[ A₁ = \text{Excess wall thickness in run} = d₀ \times (t₀ - tᵣ₀) \]  
\[ (in^2) \]
\[ A₂ = \text{Excess wall thickness in branch} = 2L*(tᵣ₀ - tᵣ₀) \]  
\[ (in^2) \]
\[ A₃ = \text{Area provided by deposited weld metal beyond OD of run and branch} \]  
\[ (in^2) \]
\[ A₄ = \text{Area provided by a reinforcing ring or pad} = (Dᵣ - d₀) \times tᵣ \]  
\[ (in^2) \]
\[ A₅ = \text{Area provided by a reinforcing saddle} = (Dᵣ - d₀) \times tᵣ \]  
\[ (in^2) \]

Total Area Provided: \[ A_{prov} = A₁ + A₂ + A₃ + (A₄ \text{ or } A₅) \]  
\[ (in^2) \]

5. Acceptability of Thinning at Reinforcement Area

Acceptable if \[ A_{prov} \geq A_{req} \]  
Yes
Attachment 7.5  Plant Specific Allowable Stress Factors

The following plant specific factors are for a typical piping system. It should be noted that some particular piping systems might have different factors. In such case, the particular factors for that piping system shall be used.

Allowable Stress Factors (1)

<table>
<thead>
<tr>
<th>Site</th>
<th>Normal $K_{Nor}$</th>
<th>Upset $K_{Upe}$</th>
<th>Emergency $K_{Eng}$</th>
<th>Faulted $K_{Fau}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>IP2</td>
<td>1.0</td>
<td>1.2</td>
<td>1.8</td>
<td>1.8 (2)</td>
</tr>
<tr>
<td>IP3</td>
<td>1.0</td>
<td>1.2</td>
<td>1.8</td>
<td>1.8 (3)</td>
</tr>
<tr>
<td>JAF</td>
<td>1.0</td>
<td>1.2</td>
<td>1.8</td>
<td>2.4 (4)</td>
</tr>
<tr>
<td>PNPS</td>
<td>1.0</td>
<td>1.2</td>
<td>1.8</td>
<td>2.4</td>
</tr>
<tr>
<td>VY</td>
<td>1.0</td>
<td>1.2</td>
<td>1.8</td>
<td>2.4 (4)</td>
</tr>
</tbody>
</table>

Notes:

(1) The typical load combinations for various operating conditions are defined as follows;
   - Normal (or Design) = Pressure + Dead Weight,
   - Upset = Normal + Operational Basis Earthquake,
   - Emergency = Normal + Design Basis Earthquake or Safe Shutdown Earthquake
   Loadings such as pressure transient or pipe rupture, etc. should be added to the appropriate load combination according to the individual plant design basis.

(2) Also see Table 1.11-2 of IP2 UFSAR.
(3) Also see Table 16.1-2 of IP3 FSAR.
(4) Use of this factor is acceptable for piping included in the Mark I Program Analysis. Otherwise, use 1.8.
Attachment 7.6 Recommendation for Safety Related Moderate Energy Class 2/3 and
NON-SAFETY RELATED PIPING

Sheet 1 of 7

For non-safety-related piping, the following restrictions of Code Case N-597 and Regulatory Guide 1.147
can be ignored.

1. Thermal expansion stress need not be considered.
2. Localized wall thinning evaluation is acceptable.

It is noted that NRC approval is required to apply the local thinning evaluation to Class 1, 2, & 3 piping. For
moderate energy Class 2 & 3 piping, NRC granted unconditional acceptance to evaluation method
prescribed in ASME CC N-513-2.

Acceptable Local Wall Thickness, t_{loc}: [2.4]

A. t_{loc} can be equal to 0.9t_{min} without further calculation, or perform following steps
B. Obtain local thinning area dimensions: L, L_m, L_{min}, L_{max} (See Figure A-1)
C. Calculate pipe characteristic length, (R_{min}t_{min})^{0.5}, where R_{min} = R_0 - t_{wall}/2
D. Calculate L_{min}/(R_{min}t_{min})^{0.5}
E. Determine t_{loc}/t_{min} by performing Case 1 and 2 in order. If the limits of Case 1 and 2 are not
satisfied, determine t_{loc}/t_{min} from Column 3622.4 of Table A-1 (2).

<table>
<thead>
<tr>
<th>Case</th>
<th>Conditions</th>
<th>Applicable Limits</th>
<th>t_{loc}/t_{min}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Limited Transverse Extent</td>
<td>(R_{min}t_{min})^{0.5} ≥ L_{min}</td>
<td>From Column 3622.2 of Table A-1</td>
</tr>
<tr>
<td>2</td>
<td>Limited Axial &amp; Transverse Extent</td>
<td>2.65(R_{min}t_{min})^{0.5} ≥ L_{min} and t_{room} &gt; 1.13t_{min}</td>
<td>Larger value of 1 - 1.5(R_{min}t_{min})^{0.5}t_{room}/(t_{room}+t_{min})/L and 0.353L_{room}/(R_{min}t_{min})^{0.5}</td>
</tr>
<tr>
<td>3</td>
<td>Unlimited Transverse Extent</td>
<td>Case 1 or Case 2 not met</td>
<td>From Column 3622.4 of Table A-1</td>
</tr>
</tbody>
</table>

F. Local Wall Thickness Requirements

<table>
<thead>
<tr>
<th>Hoop Stress Criteria</th>
<th>Actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>t_p ≥ t_{loc}</td>
<td>Accept for Hoop stress</td>
</tr>
<tr>
<td>t_p &lt; t_{loc}</td>
<td>Repair or replace</td>
</tr>
</tbody>
</table>

Notes:
1. For multiple thinned areas, the wall thickness is required to exceed t_{min} for a distance that is the greater of
   2.5(R_{wall}-t_{wall})^{1.5} or 2L_{adj}, between adjacent thinned regions. Otherwise, the adjacent thinned areas shall be
   considered as a single thinned region in the evaluation.
2. For multiple thinned areas, the wall thickness shall exceed t_{min} for an axial distance the greater of 2.5(R_{wall}-t_{wall})^{1.5} or
   2L_{adj}, between adjacent thinned regions. Otherwise, the adjacent thinned areas shall be considered as a single
   thinned region in the evaluation.
### Attachment 7.6 Recommendation for Safety Related Moderate Energy Class 2/3 and Non-Safety Related Piping

### Table A-1

<table>
<thead>
<tr>
<th>$\sqrt{R_{\text{mid}}} / d$</th>
<th>Allowable Local Thickness</th>
<th>$L_{\text{local}} / L_{\text{min}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.100</td>
<td>0.100</td>
</tr>
<tr>
<td>0.20</td>
<td>0.100</td>
<td>0.261</td>
</tr>
<tr>
<td>0.23</td>
<td>0.100</td>
<td>0.300</td>
</tr>
<tr>
<td>0.26</td>
<td>0.100</td>
<td>0.375</td>
</tr>
<tr>
<td>0.32</td>
<td>0.100</td>
<td>0.477</td>
</tr>
<tr>
<td>0.38</td>
<td>0.100</td>
<td>0.551</td>
</tr>
<tr>
<td>0.45</td>
<td>0.100</td>
<td>0.616</td>
</tr>
<tr>
<td>0.50</td>
<td>0.100</td>
<td>0.651</td>
</tr>
<tr>
<td>0.60</td>
<td>0.100</td>
<td>0.703</td>
</tr>
<tr>
<td>0.70</td>
<td>0.182</td>
<td>0.742</td>
</tr>
<tr>
<td>0.83</td>
<td>0.300</td>
<td>0.778</td>
</tr>
<tr>
<td>0.85</td>
<td>0.315</td>
<td>0.782</td>
</tr>
<tr>
<td>0.90</td>
<td>0.349</td>
<td>0.794</td>
</tr>
<tr>
<td>1.00</td>
<td>0.410</td>
<td>0.813</td>
</tr>
<tr>
<td>1.20</td>
<td>0.505</td>
<td>0.841</td>
</tr>
<tr>
<td>1.40</td>
<td>0.572</td>
<td>0.860</td>
</tr>
<tr>
<td>1.60</td>
<td>0.622</td>
<td>0.873</td>
</tr>
<tr>
<td>1.80</td>
<td>0.659</td>
<td>0.883</td>
</tr>
<tr>
<td>2.00</td>
<td>0.687</td>
<td>0.891</td>
</tr>
<tr>
<td>2.25</td>
<td>0.714</td>
<td>0.897</td>
</tr>
<tr>
<td>2.50</td>
<td>0.734</td>
<td>0.900</td>
</tr>
<tr>
<td>2.75</td>
<td>0.750</td>
<td>0.900</td>
</tr>
<tr>
<td>3.00</td>
<td>0.763</td>
<td>0.900</td>
</tr>
<tr>
<td>3.50</td>
<td>0.787</td>
<td>0.900</td>
</tr>
<tr>
<td>4.00</td>
<td>0.811</td>
<td>0.900</td>
</tr>
<tr>
<td>4.50</td>
<td>0.834</td>
<td>0.900</td>
</tr>
<tr>
<td>5.00</td>
<td>0.858</td>
<td>0.900</td>
</tr>
<tr>
<td>5.50</td>
<td>0.882</td>
<td>0.900</td>
</tr>
<tr>
<td>6.00</td>
<td>0.900</td>
<td>0.900</td>
</tr>
<tr>
<td>&gt;6.00</td>
<td>0.900</td>
<td>0.900</td>
</tr>
</tbody>
</table>

**General Note:**
Interpolation may be used for intermediate values.

Table A-1
Figure A-1 Illustration of Nonplanar Flaw Due To Wall Thinning
Attachment 7.6 Recommendation for Safety Related Moderate Energy Class 2/3 and Non-Safety Related Piping  

Sheet 4 of 7

Figure A-2: Separation Requirements for Adjacent Thinned Areas

\[
X_{ij} = \text{minimum distance between areas } i \text{ and } j \\
L_{m, i} = \text{maximum extent of thinned area } i \\
L_{m, \text{avg}} = 0.5(L_{m, i} + L_{m, j})
\]

GENERAL NOTE:
Combination of adjacent areas into an equivalent single area shall be based on dimensions and extents prior to combination.
Attachment 7.6 Recommendation for Safety Related Moderate Energy Class 2/3 and
NON-SAFETY RELATED PIPING

Sheet 5 of 7

Figure A-3: Separation Requirements for Adjacent Thinned Areas
## Attachment 7.6: RECOMMENDATION FOR SAFETY RELATED MODERATE ENERGY CLASS 2/3 AND NON-SAFETY RELATED PIPING

<table>
<thead>
<tr>
<th>(NRC review and approval is required for Class 1 and High Energy Piping)</th>
</tr>
</thead>
</table>

### 1. Design Parameters

- **D<sub>c</sub>**: Outside Diameter, (in)
- **t<sub>nom</sub>**: Pipe nominal thickness, (in)
- **p**: design pressure [for N597-2] or maximum operating pressure at flaw location [for N-513]
- **S**: allowable stress for pipe (psi)
- **t<sub>min</sub>**: Minimum thickness required for hoop stress due to pressure, \( t = \frac{pD}{2(S + 0.4p)} \) (in)
- **t<sub>p</sub>**: Minimum predicted wall thickness at next inspection, (in)
- **\( \sigma_c \)**: nominal pipe longitudinal bending stress resulting from all primary pipe loading (psi)
- **R<sub>min</sub>**: Pipe mean radius, \( R = \frac{D}{2} \), (in)
- **R<sub>p</sub>**: Pipe radius, \( R = \frac{D}{2} \), (in)

### 2. Local Thinning Area Dimensions (See Figure 2 for illustration)

- **L**: Maximum length of area where thickness is less than \( t_{min} \) (in)
- **L<sub>L</sub>**: Maximum length of area where thickness is less than \( t_{p} \) (in)
- **L<sub>transverse</sub>**: Maximum length in transverse direction of area where thickness is less than \( t_{min} \) (in)
- **L<sub>axial</sub>**: Maximum length in axial direction of area where thickness is less than \( t_{min} \) (in)
- **L<sub>eval</sub>**: Dimensionless length of local thinning in axial direction

**Note:** For N513-2, apply to pipe & fitting at a distance <= \( (R_{n})^{0.5} \) from weld center line

### 3. Acceptance Thickness for Local Thinning, \( t_{sec} \)

- \( (R^{*})^{0.5} \): Pipe characteristic length, (in)
- **Case 1:** Local Thinning for Limited Transverse Extent
  - Applicable if \( (R^{*})^{0.5} \geq L_{in} \)
  - Applies to: (see note 1)
  - \( c_1 = \frac{(t_{sec})}{t_{nom}} \)

**Note 1:** N513-2: from curve 1 of Fig. 3 if applicable; N597-2: from table 3622-1, 3622.2 if applicable

- **Case 2:** Local Thinning for Limited Axial and Transverse Extent
  - Applicable if \( 2.65(R^{*})^{0.5} \geq L_{in} \) and \( t_{nom} > 1.13t_{min} \)
  - \( c_2 = \frac{(1.5(R^{*})^{0.5})^{2}}{(L_{in})^{2}} + 1.0 \)
  - \( c_3 = 0.35(L_{in})^{2} \)

**Note 2:** N513-2: from curve 2 of Fig. 3; N597-2: from table 3622-1, 3622.4

- **Case 3:** Unlimited Transverse Extent
  - \( c_3 = \frac{(t_{sec})}{t_{nom}} \)

- **Note 2:** N513-2: from curve 2 of Fig. 3; N597-2: from table 3622-1, 3622.4

- **Acceptable if \( t_{sec} \geq t_{sec} \)**

### b. Elbow and Bent Pipe
### Attachment 7.6 Recommendation for Safety Related Moderate Energy Class 2/3 and NON-SAFETY RELATED PIPING

#### Sheet 7 OF 7

**b. Elbow and Bent Pipe**

- **R₀**: Elbow radius, (in)
- **θ**: Thinning location angle, See Fig. 2 for illustration (Deg.)
- **tₑₒₑ**: (0.5+0.5/(1+(Rₑₒₑ/R₀*cosθ))) * tₑₒₑ, (in)

<table>
<thead>
<tr>
<th>R₀</th>
<th>θ</th>
<th>tₑₒₑ</th>
<th>Acceptable if tₑ ≥ tₑₒₑ</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>0</td>
<td>0.128</td>
<td>yes</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>dₒ</th>
<th>Dₒ</th>
<th>α</th>
<th>tₑₒₑ</th>
<th>Acceptable if tₑ ≥ tₑₒₑ</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>24</td>
<td>45</td>
<td>0.103</td>
<td>yes</td>
</tr>
</tbody>
</table>

**Notes applicable to Code Case N597-2:**

1. At the reinforcement area of opening for any branch connection or tee on the run piping. The reinforcement area is a region adjacent to the branch connection on the run piping, unless the distance between the center of the branch connection and the edge of the thinning area predicted to be less than tₑₒₑ exceeds Dₒ, where Dₒ is the nominal inside diameter of the branch connection.
2. At the small end transition of a reducer.
3. Inner portion of elbows, tₑₒₑ = 0.5[1+1/(1+(Rₑₒₑ/R₀)cosθ)]tₑₒₑ, see details in Section 3622.1 (3) of [2.4].

2. **Case 1 shall not be used to evaluate a reducer.** For the rule of the separation, see details in Section 3622.2(a) of [2.4].

3. **Case 2 is not applicable for the following conditions:**
   1. Thinned area overlaps the reinforcement of the branch connection.
   2. Thinned area lies on the conical or small diameter transition zone of a reducer.
   3. Adjacent thinned area qualified by this approach when the reinforcement zones associated with each area would overlap.

4. **As an alternative, Oₑₒₑ = 1 - 0.935Aₑₒₑ/(Lₑₒₑ*tₑₒₑ),** where Aₑₒₑ = the reinforcement area available in the pipe wall based on tₑₒₑ distribution in excess of tₑₒₑ and within the limits of reinforcement of B31.1 Code, see Section 3622.3(d) of [2.4].

5. **Case 3 shall not be used to evaluate a reducer.** For the rule of the separation requirements for adjacent thinned area, see details in Section 3622.5(a) of [2.4].
Wear rate calculations fall into two categories. The first category is for components without baseline or previous inspection data (i.e., no initial thickness data is available for the component). The second category is for components which have initial (baseline) thickness data or data is available from previous inspections.

Due to uncertainties in original thickness, operating history, UT measurement errors, and other factors, establishing accurate wear rates can be difficult. It requires some judgment. EPRI has developed methodologies for wear rate calculations on both initial and repeat inspections. These are described in detail in Section 4.6 of Reference 2.16.

There are four methods commonly used for determining wear of piping components from UT inspection data. The methods are:

**Band Method**

The band method is based on the assumption that wear caused by FAC is localized and the thickness variations observed around circumferential bands is an indication of wear experienced by the component. The inspection data is divided into circumferential bands of one grid width each.

The initial thickness \( t_{\text{init}} \) of each band is assumed to be the larger of the nominal thickness or the maximum thickness found in each band \( t_{\text{max}} \). The band wear is the initial thickness minus the minimum thickness found in the band \( t_{\text{meas}} \).

For each band: 

\[ t_{\text{init}} = \text{larger of } t_{\text{nom}} \text{ or } t_{\text{max}} \]

\[ \text{Wear} = t_{\text{init}} - t_{\text{meas}} \]

The component maximum wear is the largest of the individual band wear values. The component initial thickness is then taken as the initial thickness of the band of maximum wear. The use of the nominal wall thickness in the calculations above address the possibility that the entire band may have thinned uniformly, which may have caused most or all of the thickness to be under nominal wall thickness.

**Area Method**

The area method uses a local rectangular region, identified as the wear region. It is based on the assumption that the entire wear area, and a thickness representative of the initial thickness, is encompassed within the rectangular region. More than one area can be defined for a given component. The initial thickness \( t_{\text{init}} \) of each area is assumed to be the larger of the nominal thickness or the maximum thickness found in each area, \( t_{\text{max}} \).

For each area: 

\[ t_{\text{init}} = \text{larger of } t_{\text{nom}} \text{ or } t_{\text{max}} \]

\[ \text{Wear} = t_{\text{init}} - t_{\text{meas}} \]

The component maximum wear is the largest of the individual area wear values. The component initial thickness is then taken as the initial thickness of the area of maximum wear. The use of the nominal wall thickness in the calculations above address the possibility that the entire area may have thinned uniformly, which may have caused most or all of the thickness to be under nominal wall thickness.
**Moving Blanket Method**

The moving blanket method in CHECWORKS is a refinement of the Area Method. It automates the process of identifying the region of maximum wear and attempts to minimize the effect of measurement errors. The method uses a predetermined size wear area or "blanket". The data within the blanket is evaluated to estimate both the initial thickness and the wear. The blanket is then moved to another location on the component and the process is repeated. The process continues until all possible locations on the component have been covered.

**Point to Point Method**

The Point to Point Method can be used when data taken at the same grid locations exists from two or more outages (or baseline data plus data from one or more outages). The wear at each location is the thickness taken at the earlier inspection minus the thickness taken at the later inspection. The largest of the grid wear values is the component maximum wear between the two outages. The Point to Point Method does not estimate the initial component thickness.

**Wear Rates for Components Without Prior Inspection Data (Initial Inspections)**

When no initial thickness data is available some value must be used for the initial wall thickness in the wear rate calculation. Variations in the component wall from the manufacturing process can impact the wear rate calculations. This is most evident in reducers and in 90 degree wrought elbows.

The Band Method, Area Method, and the Moving Blanket Method can be used to evaluate components with single inspection data. All the methods are based on the theory that the wear caused by FAC is typically found in a localized area or region.

The following table taken partially from Reference 2.17 shows the recommended methods and the limitations for each method to determine wear on components with single outage inspection data. Only methods marked "YES" in the table below are recommended to be used for components with single outage inspection data.

<table>
<thead>
<tr>
<th>Component Type</th>
<th>Band Method</th>
<th>Area Method</th>
<th>Moving Blanket Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elbow</td>
<td>NO</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>Tee</td>
<td>YES (*)</td>
<td>NO</td>
<td>YES (*)</td>
</tr>
<tr>
<td>Straight Pipe</td>
<td>YES</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>Concentric Reducer/Expander</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>Eccentric Reducer/Expander</td>
<td>NO</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>Nozzle</td>
<td>YES (*)</td>
<td>NO</td>
<td>NO</td>
</tr>
</tbody>
</table>

* Initial thickness and measured wear determined from single outage inspection data should be interpreted conservatively and only be used for structural integrity.

Alternately, a conservative Wear and Wear Rate may be calculated as follows:
The lowest recorded thickness value for all grid points is used as the measured thickness ($t_{\text{meas}}$).

$$t_{\text{meas}} = \text{larger of } t_{\text{min}} \text{ or } t_{\text{max}}$$

Wear = $t_{\text{vel}} - t_{\text{meas}}$

Wear Rate ($W_r$) = Wear / Time

**Wear Rate for Components With Baseline or Prior Inspection Data (Repeat Inspections)**

Multiple inspection data are considered valid only if the identical grids were used for each inspection. The "point-to-point" method is used to calculate the component wear rate. The wear at each grid location is the thickness taken at the earlier inspection minus the thickness taken at the later inspection. The largest of the grid wear values is the component maximum wear between the two outages.

The following methods for calculating total wear from multiple inspections are recommended by EPRI in Reference 2.17.

### TABLE 2

<table>
<thead>
<tr>
<th>Cases</th>
<th>Moving Blanket</th>
<th>Point-to-Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline data and subsequent outages</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>No baseline data with 1 or 2 outages</td>
<td>YES</td>
<td>YES [1]</td>
</tr>
<tr>
<td>No baseline data with more than 2 outages</td>
<td>YES [2]</td>
<td>YES [3,4]</td>
</tr>
</tbody>
</table>

[1] Point-to-point method can be used when there is data from at least two outages. However, the wear rate should be compared to the lifetime wear rate obtained from single inspection (Table 1). The maximum wear rate obtained from Table 1 and 2 should be used to determine acceptability of the component. Care must be taken when using the point to point method in cases where the wear between the outages is small. Two large numbers (wall thickness) are subtracted to obtain a small number (wear since previous outage) and then divided by another relatively small number (interval between outages) to determine the wear rate. UT measurement inaccuracies could cause significant calculation error with this method. However, in most cases where inspection data from several inspection outages is available, the point to point method will provide more accurate determinations of wear than other methods.

[2] Use single inspection method (Table 1) at first inspection plus Point-to-Point method thereafter.
**Attachment 7.8: Guide for using PS-S-001 as informational attachment**

<table>
<thead>
<tr>
<th>PS-S-001 Attachment</th>
<th>Title</th>
<th>Acceptability</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>References for pipe wall thinning (PWT) and crack-like flaw evaluation (CLFE).</td>
<td>Yes (see Attachment 7.9)</td>
<td>References are either built into section 2.0 or the spread sheets in the EN standard.</td>
</tr>
<tr>
<td>II</td>
<td>Terminology and Nomenclature for PWT and CLFE</td>
<td>Yes (see Attachment 7.9)</td>
<td>Nomenclature is either built into section 3.0 or the spread sheets in the EN standard.</td>
</tr>
<tr>
<td>III</td>
<td>Inputs / Requirements common for PWT and CLFE</td>
<td>Yes (see Attachment 7.9)</td>
<td>Inputs are built into the spread sheets in the EN standard.</td>
</tr>
<tr>
<td>IV</td>
<td>Inputs / Requirements for evaluation of PWT</td>
<td>Yes (see Attachment 7.9)</td>
<td>Inputs are built into the spread sheets in the EN standard.</td>
</tr>
<tr>
<td>V</td>
<td>Inputs / Requirements for CLFE</td>
<td>Yes (see Attachment 7.9)</td>
<td>Inputs are built into the spread sheets in the EN standard.</td>
</tr>
<tr>
<td>VI</td>
<td>Definition of PWT and CLFE</td>
<td>Yes (see Attachment 7.9)</td>
<td></td>
</tr>
<tr>
<td>VII (removed)</td>
<td>PWT Evaluation: Code Evaluation Procedure</td>
<td>No CC N-480 was superseded</td>
<td>See Figure 1, Att. 7.1, 7.2, 7.6 in the EN standard.</td>
</tr>
<tr>
<td>VIII (removed)</td>
<td>PWT Evaluation: NRC Generic Letter 90-05 Methods</td>
<td>No, CC N-480, methodology required NRC approval</td>
<td>See Figure 1, Att. 7.1, 7.2, 7.6 for wall thinning, Att. 7.3 for through-wall flaw in the EN standard. Unconditional NRC acceptance using CC N-513-2 for moderate energy class 2 &amp; 3 piping.</td>
</tr>
<tr>
<td>IX (removed)</td>
<td>PWT Evaluation: Alternate Methods</td>
<td>No CC N-480 was superseded</td>
<td>EN standard is based on CC N-597-2. The code is applicable to non-planar flaws. Att. 7.6 need NRC approval when Class 1, 2 &amp; 3 piping local thinning ( t_{\text{sec}} &lt; t_p &lt; t_{\text{min}} ) evaluation. Moderate energy class 2 &amp; 3 piping does not need to have NRC approval.</td>
</tr>
</tbody>
</table>
Attachment 7.8: Guide for using PS-S-001 as informational attachment

Page 2 of 2

<table>
<thead>
<tr>
<th>X</th>
<th>PWT Evaluation: Finite Element Analysis Methods</th>
<th>Yes (see Attachment 7.9), need editorial update</th>
<th>See Att. 7.2 in the EN standard, 2D finite element method will solve majority of the cases.</th>
</tr>
</thead>
<tbody>
<tr>
<td>XI</td>
<td>CLFE: Section XI Flaw Evaluation Standards</td>
<td>Yes (see Attachment 7.9) From EPRI &amp; Sect. XI documents</td>
<td>For moderate energy piping, use ATT. 7.3B in the EN standard for through-wall flaw.</td>
</tr>
<tr>
<td>XII</td>
<td>CLFE: Procedure for Austenitic Piping</td>
<td>Yes (see Attachment 7.8) Safety factor changed (use as reference)</td>
<td>For moderate energy piping, use ATT. 7.3A in the EN standard for through-wall flaw.</td>
</tr>
<tr>
<td>XIII</td>
<td>Flaw Evaluation Procedure for Ferritic Piping</td>
<td>Yes (see Attachment 7.9) Safety factor changed (use as reference)</td>
<td>For moderate energy piping, use ATT. 7.3A in the EN standard for through-wall flaw.</td>
</tr>
<tr>
<td>XIV</td>
<td>CLFE: Fracture Mechanics Software</td>
<td>Yes (see Attachment 7.9) Safety factor changed (use as reference)</td>
<td></td>
</tr>
<tr>
<td>XV</td>
<td>CLFE: Alternate Fracture Mechanics Solutions</td>
<td>Yes (reference)</td>
<td></td>
</tr>
<tr>
<td>XVI</td>
<td>Derivation of Approaches for PWT Evaluation Given in Attachment VII</td>
<td>No CC N-480 was superseded</td>
<td></td>
</tr>
<tr>
<td>XVII</td>
<td>Figures</td>
<td>Yes, Fig. 1 &amp; 3 Figure 2 is no longer valid and k value changed</td>
<td>Use figure 1 of the EN standard instead of Figure 2 of PS-S-001</td>
</tr>
</tbody>
</table>
REFERENCES

A. Additional References Used in This Standard and Attachments:


A.7 ANSI B31.1 - 1973, with all addenda up to and including Winter 1973 Addenda.


A.35 Intentionally Left Blank.


B. References Provided For Information:


B.5 EOI formulations using Fracture Mechanics Approach.


Attachment II: Terminology and Nomenclature for Pipe Wall Thinning And Crack-Like Flaw Evaluation

a  Maximum depth of surface flaw, inch
ar  Final flaw size, inch
A  Corrosion allowance, inch (includes any additional wall thickness for general loss)
A1  Area of wall thinning that exceeds \( l_m \), inch\(^2\)
A2  Compensating area for local wall thinning, inch\(^2\)
Ai  Internal Area of pipe, in\(^2\)
\( \alpha \)  Coefficient of thermal expansion of pipe;
          Maximum cone angle at the center of the reducer, degrees
B1, B2  Primary stress indices
\( \beta \)  Angle to neutral axis of flawed pipe, radians
\( c \)  Half length of surface flaw, inch
CVN  Charpy V-notched absorbed energy, ft-lb
\( d_{11}, d_{22} \) Depth of flaws as shown in figures of generic letter 90-05 evaluations, inch
\( d_{cp} \) Distance from the pipe nominal center to the center of pressure for the thinned section, inch
\( d_{og} \) Distance from the pipe nominal center to the centroid of the pipe wall metal at the thinned section, inch
\( D_a \) Mean Diameter of corroded pipe and outer pipe, inch
\( D_i \) Nominal pipe internal diameter, inch
\( D \) Nominal pipe diameter, inch
\( D_N \) Inside diameter of corroded pipe, inch
\( D_o \) Outside pipe diameter, inch
\( D_p \) Inside pipe diameter based on projected pipe wall thickness, inch
\( D_l \) Outside diameter at the large end of the reducer, inch
\( D_s \) Outside diameter at the small end of the reducer, inch
\( E \) Modulus of elasticity or weld joint efficiency, psi
\( E_c \) Modulus of elasticity at room temperature, psi
\( E_t \) Modulus of elasticity at pipe temperature, psi
\( f \) Stress range reduction factor for cyclic conditions
F  Boundary correction factor or a parameter for normalized (axial) flaw stress intensity factor
Attachment 7.9: Informational Attachment
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A parameter for circumferential flaw bending stress intensity factor

A parameter for circumferential flaw membrane stress intensity factor

Flow Accelerated Corrosion

Generic term used to describe cracking or locally thinned area of a pipe wall

Gas Tungsten Arc Welding

Gas Metal Arc Welding

Code stress intensification factor, 0.75 ≤ 1

Predicted minimum centroidal moment of inertia at the pipe section, in^4

Measure of material toughness due to crack extension at upper shelf, transition, and lower shelf temperatures, J integral at first flaw extension, in-lb/in^2

Measure of fracture toughness at 1 mm of crack growth at upper shelf temperature, in-lb/in^2

Applied Fracture Toughness, ksi \( \sqrt{\text{in}} \)

Mode I stress intensity factor for bending loading, ksi \( \sqrt{\text{in}} \)

Critical Fracture Toughness, ksi \( \sqrt{\text{in}} \)

A component of the screening criterion (SC), the ratio of the stress intensity factor to material toughness

Mode I stress intensity factor for membrane loading, ksi \( \sqrt{\text{in}} \)

Total flaw length, inch

Length of locally thinned area less than \( t_m \) inch

Maximum length of thinned area less than \( t_m \) inch

Axial length of locally thinned area less than \( t_m \) inch

Tangential (transverse) length of locally thinned area in less than \( t_m \) inch

Minimum \( L_m \) measured, inch

Length of reinforcement area, inch

Margin of stress

Resultant moment loading due to weight and other sustained loads, in-lb

Resultant loading moment due to occasional load, in-lb

Range of resultant moment due to thermal expansion, in-lb

Microbiologically Induced Corrosion

Number of cycles

Internal (or external) design pressure, psi
Attachment 7.9: Informational Attachment

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Total axial load including pressure, kip (see Att. XIII)

- \( P_b \) Applied primary bending stress, psi
- \( P_e \) Applied expansion stress, psi
- \( P_m \) Primary membrane stress at flaw location, psi
- \( P_n \) Normal operating pressure, psi
- \( P_o \) Maximum internal operating pressure (peak pressure), psi
- \( P_{LA} \) Total axial load on pipe including pressure, lb
- \( r \) Radius of opening in a pipe (for pipe branch reinforcement), inch
- \( R \) Mean pipe radius, inch
- \( R_b \) Elbow bend radius, inch
- \( R_o \) Outside pipe radius, inch
- \( R_l \) Ratio of \( Z_n \) to \( Z_1 \)
- \( R_1 \) Ratio of \( t_n \) to \( t_1 \)
- \( R_i \) Internal Radius, inch
- \( R_n \) Mean pipe radius based on nominal pipe diameter, inch
- \( R_m \) Mean pipe radius based on minimum pipe wall thickness as determined for hoop pressure, inch
- \( R_{mn} \) Mean pipe radius based on wall thickness \( t_m \)
- \( S \) Maximum allowable stress at design temperature in ASME Code hoop stress equation, psi
- \( S_A \) Allowable stress range for expansion stress in Code stress equations 10 and 11, psi
- SAW Submerged Arc Welding
- SMAW Shielded Metal Arc Welding
- \( S_g \) Basic material allowable stress at cold temperature, psi
- SC Screening Criterion
- SE Maximum allowable stress in material due to internal pressure at design temperature and joint efficiency \( E \), psi
- \( S_h \) Basic material allowable stress at design (hot) temperature in ASME Code stress equations 8, 9 and 11, psi
- \( S_L \) Distance between multiple flaws in GL 90-05 evaluation, inch
- \( S_{LP} \) Longitudinal pressure stress from internal pressure, psi
- \( S_m \) Design stress intensity at design / operating temperatures, psi
- \( S_{OL} \) Maximum design stress due to occasional loads, psi
Attachment 7.9: Informational Attachment

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\[ S'_r \] A component of screening criteria (SC), the ratio of the sum of primary bending and expansion stresses to the bending stress at limit load

\[ S_{sl} \] Maximum design stress due to sustained loads, psi

\[ S_e \] Thermal expansion stress, psi

\[ S_{TE} \] Maximum design stress due to sustained loads plus thermal expansion, psi

\[ \sigma \] Bending stress at the flawed location for dead weight, pressure, thermal expansion, and SSE as used in GL 90-05, psi

\[ \sigma_0 \] Reference bending stress at the limit load, psi

\[ \sigma_u \] Material ultimate strength, psi

\[ \sigma_y \] Material yield stress, psi

\[ \sigma_{yt} \] Material yield stress at temperature, psi

\[ t \] Nominal pipe wall thickness, inch

\[ t_{loc} \] Allowable local wall thickness, inch

\[ t_{ap} \] Average projected thickness remote from flaw location, inch

\[ t_p \] Uniform thickness of piping with outside diameter \( D_o \) required to withstand sustained and occasional bending loadings as considered in the design analysis of record, in the absence of pressure, anchor movement and thermal expansion loadings, inch

\[ t_m \] Code minimum wall thickness satisfying hoop stress criteria, inch

\[ t_{min} \] Minimum pipe wall thickness based on Code Equations for axial pressure and bending, inch

\[ t_{l} \] Larger of \( t_m \) and \( t_{min} \), inch

\[ t_{n,1} \] \( t_m \) for large end of reducer, inch

\[ t_{n,2} \] \( t_m \) for small end of reducer, inch

\[ t_n \] Nominal pipe wall thickness, inch

\[ t_p \] Minimum projected pipe wall thickness at the next scheduled inspection, inch

\[ T \] Pipe design temperature, °F

\[ T_{d}(T_e) \] Range of temperature on side \( a(b) \) of gross structural discontinuity or material discontinuity, °F (see ASME Section III NB 3653)

\[ \theta \] One-half of the final flaw angle, radian

\[ v \] Poisson Ratio

\[ x \] \( a/t \)

\[ Y \] Coefficient 0.4 for temperature 900°F and below

\[ Z_p \] Section modulus based on projected pipe wall thickness \( t_p \), inch³

\[ Z_M \] Predicted minimum section modulus for the thinned section, inch³
Attachment 7.9: Informational Attachment

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\[ Z_n \]  
Section modulus based on nominal wall thickness \( t_n \), inch\(^3\)
The information contained in the following tables is considered as given conditions and known values. The purpose of collecting this information is to perform an acceptability evaluation of locally thinned areas (indications) and crack-like flaws.

Table 1: Location and Other Piping Information
Relating to the Indication or Flaw

<table>
<thead>
<tr>
<th>Component or Subcomponent Location:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location: Plant System</td>
</tr>
<tr>
<td>Location: Building</td>
</tr>
<tr>
<td>Location: Elevation</td>
</tr>
<tr>
<td>Location: Other Details, if any</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Piping or Component:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description: Pipe / Branch / Tee / Elbow / Reducer or other</td>
</tr>
<tr>
<td>Line Class: ASME Class 1, 2, 3 or ANSI B31.1</td>
</tr>
<tr>
<td>ANSI B31.7 Class 1, 2, 3 or</td>
</tr>
<tr>
<td>Section XI Line Class: Class 1, 2, 3 Non-Safety</td>
</tr>
<tr>
<td>Iso Drawing No.</td>
</tr>
<tr>
<td>P&amp;ID or Other Id No.</td>
</tr>
<tr>
<td>Stress Problem No.</td>
</tr>
<tr>
<td>Line No.</td>
</tr>
<tr>
<td>Node No(s) Used In the Stress Math Model</td>
</tr>
<tr>
<td>Type of Piping: CS / SS</td>
</tr>
<tr>
<td>Component Identification No.</td>
</tr>
</tbody>
</table>
## Table 2: Other Piping Related Information Required for Localized Pipe Wall Thinning and Crack-Like Flaw Evaluation:

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Ultimate Strength ($\sigma_u$)</td>
<td>psi</td>
</tr>
<tr>
<td>Material Yield Stress ($\sigma_y$)</td>
<td>psi</td>
</tr>
<tr>
<td>Material Yield Stress at Temperature ($\sigma_yT$)</td>
<td>psi</td>
</tr>
<tr>
<td>Modulus of Elasticity ($E$)</td>
<td>psi</td>
</tr>
<tr>
<td>Modulus of Elasticity at Room Temperature ($E_C$)</td>
<td>psi</td>
</tr>
<tr>
<td>Modulus of Elasticity at Pipe Temperature ($E_t$)</td>
<td>psi</td>
</tr>
<tr>
<td>Coefficient of Thermal Expansion of Pipe Material over a range from 70°F to Temperature ($\alpha$)</td>
<td></td>
</tr>
<tr>
<td>Poisson's Ratio ($\nu$) at all Temperatures</td>
<td></td>
</tr>
<tr>
<td>Applied Fracture Toughness ($K_{IA}$)</td>
<td>ksi $\sqrt{in}$</td>
</tr>
<tr>
<td>Critical Fracture Toughness ($K_{IC}$)</td>
<td>ksi $\sqrt{in}$</td>
</tr>
</tbody>
</table>

* Information required for Fracture Mechanics Evaluation of Crack-like Flaws
### Table 3: Material and Geometry of the Pipe and Description of Weld:

<table>
<thead>
<tr>
<th>Material of Pipe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specification</td>
</tr>
<tr>
<td>Type or Grade</td>
</tr>
<tr>
<td>Class</td>
</tr>
<tr>
<td>Product Form</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Geometry of Pipe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal diameter (d) inch</td>
</tr>
<tr>
<td>Schedule</td>
</tr>
<tr>
<td>Pipe O.D. (D_o) inch</td>
</tr>
<tr>
<td>Nominal thickness (t) inch</td>
</tr>
</tbody>
</table>

**If Weld is Involved for Pipe Wall Thinning or Crack-like Flaw Evaluation:**

| Location of Weld with respect to the Pipe Flaw and any Pipe Discontinuity |
| Type of Weld.                  |
Table 4: Loading Parameters:

<table>
<thead>
<tr>
<th>PIPING PRESSURES (psi):</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Operating ($P_n$)</td>
</tr>
<tr>
<td>Maximum Operating ($P_o$)</td>
</tr>
<tr>
<td>Internal Design (P)</td>
</tr>
<tr>
<td>External Design, if applicable (P) (eg., Condenser Lines)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PIPING TEMPERATURES (°F):</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating</td>
</tr>
<tr>
<td>Maximum Operating</td>
</tr>
<tr>
<td>Design (T)</td>
</tr>
</tbody>
</table>

HIGH ENERGY PIPING CONSIDERATIONS

- Is Piping High Energy ($T > 200\,^{\circ}\text{F}$ and $P > 275$ psig)  
  or  
- Moderate Energy ($T \leq 200\,^{\circ}\text{F}$ or $P \leq 275$ psig)

SEISMIC CATEGORY: (I, II, III)

RESULTANT MOMENT LOADINGS (in-lb)  
(For Class 2 & 3 and B31.1) *  
Due to Weight and Other Sustained Loads ($M_\lambda$)  
Due to Occasional Loads ($M_\phi$)  
Due to Thermal Expansion Loads ($M_c$)

RESULTANT MOMENT LOADINGS (in-lb)  
(For Class 1) *

* In some cases there may be multiple loading conditions that have to be considered.
### ALLOWABLE PIPING STRESSES (psi):

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 1 and B31.7 Piping:</td>
<td></td>
</tr>
<tr>
<td>Design Stress Intensity ($S_T$) at Design / Operating Temperature</td>
<td></td>
</tr>
<tr>
<td>Class 2, 3 and B31.1 Piping</td>
<td></td>
</tr>
<tr>
<td>Maximum Allowable Stress at Design Temperature in Code Hoop Stress Equations ($S$)</td>
<td></td>
</tr>
<tr>
<td>Basic Material Stress at Cold Temperature ($S_C$)</td>
<td></td>
</tr>
<tr>
<td>Basic Material Allowable Stress at Design (hot) Temperature ($S_H$) in Code Stress Equations 8, 9 and 11</td>
<td></td>
</tr>
<tr>
<td>Allowable Stress Range for Expansion Stress ($S_A$) in Code Stress Equations 10 and 11</td>
<td></td>
</tr>
<tr>
<td>Weld Joint Efficiency ($E$)</td>
<td>*</td>
</tr>
</tbody>
</table>

* Required For Pipe Wall Thinning (Indication) Evaluation
### Table 6: Applicable Codes for the Evaluation of Indications and Flaws:

<table>
<thead>
<tr>
<th>PLANT:</th>
<th>Ref. No.</th>
<th>CODE</th>
<th>Check Applicable Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANO-1</td>
<td>A.10</td>
<td>Repair &amp; Replacement: ASME Section XI, 1986 Ed. w/o Addenda.</td>
<td></td>
</tr>
<tr>
<td>ANO-2</td>
<td>A.3</td>
<td>ASME Boiler and Pressure Vessel Code, Section III, Subsections NB, NC, ND 1971 with Summer 1971 Addenda</td>
<td></td>
</tr>
<tr>
<td>ANO-2</td>
<td>A.10</td>
<td>ISI: ASME Section XI, 1986 Ed. w/o Addenda.</td>
<td></td>
</tr>
<tr>
<td>ANO-2</td>
<td>A.11</td>
<td>Repair &amp; Replacement: ASME Section XI, 1986 Ed. w/o Addenda.</td>
<td></td>
</tr>
<tr>
<td>GGNS</td>
<td>A.1</td>
<td>ASME Boiler and Pressure Vessel Code, Section III, Subsections NB, NC, ND 1974, through Summer 1975 Addenda</td>
<td></td>
</tr>
<tr>
<td>GGNS</td>
<td>A.12</td>
<td>ASME Section XI, 1977 Ed. through Summer 1979 Addenda</td>
<td></td>
</tr>
<tr>
<td>RBS</td>
<td>A.1</td>
<td>ASME Boiler and Pressure Vessel Code, Section III, Subsections NB, NC, ND 1974, through Summer 1975 Addenda</td>
<td></td>
</tr>
<tr>
<td>RBS</td>
<td>A.11</td>
<td>ASME Section XI, 1980 Ed. through Winter 1981 Addenda</td>
<td></td>
</tr>
<tr>
<td>W-3</td>
<td>A.1</td>
<td>ASME Boiler and Pressure Vessel Code, Section III, Subsection NB 1974, with Summer 1975 Addenda.</td>
<td></td>
</tr>
<tr>
<td>W-3</td>
<td>A.5</td>
<td>ANSI B31.1 - 1973, with All Addenda through and including Summer 1974</td>
<td></td>
</tr>
</tbody>
</table>
Table 1: Description of Locally Thinned Area:

**Define Initiating Mechanism:**

<table>
<thead>
<tr>
<th>Corrosion Mechanisms such as:</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Flow Accelerated Corrosion (FAC)</td>
</tr>
<tr>
<td>(2) Microbiologically Induced Corrosion (MIC), Solid Particle Impingement &amp; Fouling in SSW</td>
</tr>
<tr>
<td>(3) Cavitation &amp; Flashing Downstream of Orifices, Flow Control Valves And Level Control Valves</td>
</tr>
<tr>
<td>(4) Mechanical Abrasion, Manufacturing Process, Pipe Wall Grinding, and</td>
</tr>
<tr>
<td>(5) Environmental Conditions.</td>
</tr>
</tbody>
</table>

**Geometry of Locally Thinned Area:** (see Figure 1)

<table>
<thead>
<tr>
<th>Internal or External</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Projected Wall Thickness ($t_p$), inch</td>
</tr>
<tr>
<td>Length of Locally Thinned Area Less Than $t_n$ ($L$), inch</td>
</tr>
<tr>
<td>Maximum Length of Thinned Area Less Than $t_m$ ($L_m$), inch</td>
</tr>
<tr>
<td>Axial Length of Locally Thinned Area Less than $t_m$, $L_{axial}$, inch</td>
</tr>
<tr>
<td>Tangential (transverse) Length of Locally Thinned Area Less Than $t_m$, $L_{trans}$, inch</td>
</tr>
</tbody>
</table>

Additional Information Required for Local Pipe Wall Thinning Evaluation:

1. Location of locally thinned area with respect to a fitting or weld on a specific isometric drawing.

2. Orientation circumferentially, looking downstream, with "0" being at the top and the measured length clockwise around the pipe to the center of the locally thinned area. Orientation to show the view north, south, east, or west has "0" at the north when viewed from above (plan view).

3. Detailed results of pipe wall inspection, including both as-measured and projected pipe wall thickness in both the axial and circumferential direction. The extent of the thickness mapping shall be at least $\pm R$ in the axial direction and shall include all of the thinned location in the circumferential direction.
Attachment 7.9: Informational Attachment

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Attachment V: Inputs / Requirements for Crack-Like Flaw Evaluation

Figure 1: Local Pipe Wall Thinning Parameters
Table 1: Description of the Flaw Location:

<table>
<thead>
<tr>
<th>Define Initiating Mechanism:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatigue / SCC / FAC / MIC / Other such as Mechanical</td>
</tr>
<tr>
<td>abrasion, Manufacturing process, Pipe wall surface grinding,</td>
</tr>
<tr>
<td>Environmental conditions or Other</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Geometry of Flaw Location:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe OD (D₀), inch</td>
</tr>
<tr>
<td>Nominal Pipe Wall Thickness (t), inch</td>
</tr>
<tr>
<td>Flaw Orientation</td>
</tr>
<tr>
<td>Flaw Length (l₀), inch</td>
</tr>
<tr>
<td>Maximum Flaw Depth for Surface Flaws (a), inch</td>
</tr>
<tr>
<td>Maximum Flaw Depth for Subsurface Flaws (2a), inch</td>
</tr>
</tbody>
</table>

Figures Describing Crack-like Flaws:

1. Location of flawed area with respect to a fitting or weld on a specific isometric drawing.

2. Orientation circumferentially, looking downstream, with "0" being at the top and the measured length clockwise around the pipe to the center of the locally thinned area. Orientation to show the view north, south, east, or west has "0" at the north when viewed from above (plan view).

3. Exact description of the flawed area (e.g., depth versus position along flaw, depth within the wall, etc.)

4. For multiple flaws, a map showing the location of the flaws (start and end points of the individual flaws) should be provided.
Attachment 7.9: Informational Attachment

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Attachment VI: Definition of Pipe Wall Thinning and Crack-Like Flaw Evaluation

1.0 Characterization of Flaws and Wall Thinning

1.1 Flaws and/or wall thinning may occur in nuclear plant piping due to a number of degradation mechanisms. Pipe wall degradation may occur in many different forms, ranging from general thinning (uniform loss of wall thickness) to local cracking (e.g., due to fatigue or intergranular stress corrosion cracking). This section provides guidance on how to characterize pipe wall degradation and recommends which sections of this manual may be appropriate for evaluation of the flaw or wall thinning detected by inspections.

2.0 Wall Thinning

2.1 Pipe wall thinning is characterized by a general loss of pipe wall thickness. The most common form of wall thinning is that due to erosion-corrosion (flow-accelerated corrosion). This type of degradation occurs due to a wearing away of protective metal oxides at the pipe wall, and is localized due to local flow turbulence or lack of alloying in carbon steel piping. Wall thinning can also result from general corrosion and wastage, due to wet steam erosion, flashing downstream of orifices or valves, or solid particle erosion.

2.2 The degradation can generally be quantified by a predicted minimum wall thickness at the location of interest. In cases of severe thinning, additional information may be required to quantify the transverse and axial extent of the thinning that is less than that required to meet minimum pipe wall thickness requirements.

2.3 Evaluation of wall thinning is addressed in Attachments VII to X.

3.0 Cracking

3.1 Cracking is the breakdown of the metal structure due to fatigue cycling or intergranular attack, leading to crack-like defects. There is no observable degradation at the surface of the metal, except for the evidence of cracking intersecting the metal surface. Pure cracking produces very localized stresses in the vicinity of the crack tip which lead to further growth of the cracks due to fatigue cycles (for fatigue cracking) or constant applied stresses (for intergranular stress corrosion cracking). Cracking may be either surface connected or sub-surface.

3.2 Cracks are characterized by a crack depth, crack length and orientation relative to the axis of the pipe. With this characterization, appropriate fracture mechanics models may be used to determine future crack growth and the allowable flaw size.

3.3 Attachments XI to XV address evaluation of crack-like defects.

4.0 Other Pipe Degradation

4.1 There are other corrosion mechanisms that produce pipe wall degradation that is neither thinning nor cracking.
Attachment VI: Definition of Pipe Wall Thinning and Crack-Like Flaw Evaluation

4.2 Pitting corrosion may occur as a result of certain material and water chemistry combinations. It is generally characterized by relatively deep local defects, although there may also be some general loss of pipe wall thickness. In many cases, the presence of pitting is discovered by local leakage through the pipe wall. The pits may be extremely localized or they may exhibit characteristics of a general indentation of the wall surface. In general, there will be adjacent areas which are affected by the pitting phenomenon, such that inspection of adjacent areas is required when pitting is discovered.

4.3 Microbiologically induced corrosion (MIC) is another form of degradation caused by microbial action at the pipe inside surface. The effect may be a general loss of pipe wall material beneath microbial scale or tubercles. For some cases, MIC may produce local pits that will lead to through-wall leakage.

4.4 In general, these other types of local wall degradation can be evaluated as wall thinning as described in Attachments VII to X. Of special interest would be evaluations using local wall thinning concepts of area reinforcement (such as is used for branch piping connections). However, in certain cases, evaluating the defect as a crack-like defect may also produce an acceptable answer (such as is used in the "through-wall flaw" approach in Attachment VIII).
1.0 INTRODUCTION

1.1 The option of using finite element element analysis is provided primarily as a "last gasp" alternative when the methods described in Attachments VII through IX are either not applicable or because they fail to provide adequate relief due to conservative simplifying assumptions which form the basis of these methods. The following conservatisms regarding calculation of hoop stresses in the EPRI NP-5911SP methodology, which also exist in Code Case N-480, and Generic Letter 90-05 can be reduced by use of finite element analysis:

1.1.1 The Local Membrane and B31.G methods are based on the assumption that the nominal pipe wall thickness $t$ is equal to the minimum wall thickness required for internal pressure, $t_m$, and no credit for $t_n > t_m$ is taken.

1.1.2 As can be seen in Figure 5 attachment IX, it is assumed in the Branch Reinforcement method that the area which must be replaced ($A_t$) is equal to $(t_m - t_n)t_m$. Depending on the shape of the locally thinned area, the true value of $A_t$ may be significantly less than this. In addition, the area available for reinforcement, $A_B$, is conservatively calculated, with not all of the local area with a projected wall thickness greater than $t_m$ being included.

1.2 For the calculation of axial stresses due to internal pressure and bending moment, it is assumed in NP-5911SP, Code Case N-480, and Generic Letter 90-05 that the pipe wall is uniformly thinned to the projected wall thickness $t_p$ for the entire 360 degree circumference. If a three dimensional (3D) finite element model is used, the variation of wall thickness around the pipe circumference can be accurately modeled.

1.3 Figure 1 shows a flow chart which describes the recommended procedure for evaluation of locally thinned areas by finite element analysis. The first step is to develop a finite element model of the locally thinned area. The type of model used will be dependent on the shape and extent of the locally thinned area. If the locally thinned area has a fairly constant $t_p$ around the pipe circumference, an axisymmetric (2D) finite element model should be used. A 3D finite element is best suited for locally thinned areas that are limited in the transverse extent or in the transverse and axial extent.

1.4 After development of the finite element model, internal pressure and bending moment loads are applied to the model. It is suggested that the following separate load cases be run:

1.4.1 Load Case 1: Internal pressure with no "end cap" loadings for hoop stress.

1.4.2 Load Case 2: Axial "end cap" loadings from internal pressure.

1.4.3 Load Case 3: Moment loadings from axial bending stresses.
Attachment 7.9: Informational Attachment

Attachment X: Pipe Wall Thinning Evaluation: Finite Element Analysis Methods

1.4.4 For the first case (hoop stress), some normalized value of internal pressure, such as 1, 100 or 1000 psi, is applied to the inside surface of the piping model. The ends of the piping model must be open. One end is “free” (no restraints) and the other is “fixed” (all degrees of freedom restrained). The axial length of the model should be sufficiently long so that the boundary conditions at either end will not affect the stress distribution at the locally thinned area. The only significant stresses calculated by the model for this load case will be hoop stresses, since there is no applied axial loading.

1.4.5 The second load case (for longitudinal pressure stresses), is the axial loading due to the internal pressure “end cap” force. This force is equal to the normalized internal pressure used in the first load case times the actual (effects of thinning included) inside area of the pipe. It is applied to the free end of the model as a uniformly distributed force/unit length around the full pipe circumference. It is important that the free end be at least one pipe diameter from the near edge of the locally thinned area so that accurate local stresses are calculated in the thinned area. This is also true for additional resultant bending moment loading, where the resultant bending moment is applied at the free end. A normalized value such as 1000 in-lbs is recommended. The stress analysis will typically provide actual moments on each side of the thinned region. The larger of the two moments should be applied to the finite element analysis normalized stress when performing the actual stress analysis.
1.5 Once the stress results for the three "normalized" load cases have been obtained, the maximum hoop and axial stresses at the locally thinned areas due to design and operational loadings can be obtained. Hoop stresses due to design pressure can be obtained by ratioing the results from the first load case. Axial stresses due to internal pressure, primary (mechanical) bending moments and secondary (thermal expansion, thermal anchor movements and seismic anchor movements) can be obtained by ratioing the results of the second and third load cases. Axial and hoop stresses can be obtained in this manner for all design and operating conditions defined in the licensing basis documentation for the piping.

1.6 Once the maximum hoop and axial stresses have been calculated, they must be compared with the allowable values defined in the Code of Construction. Since ASME Class 1 requires the evaluation of through-wall thermal bending stresses and a fatigue evaluation for cyclic operation, Figure 1 defines a separate evaluation procedure for Class 1 piping. This procedure is described in Section 2. The evaluation procedure recommended for ASME Class 2 and Class 3 piping and ANSI B31.1 piping is included in Section 3.

2.0 CLASS 1 PIPING EVALUATION PROCEDURE

2.1 The first step defined in Figure 1 for the Class 1 piping evaluation procedure is to check that the stress requirements for the design conditions have been met. hoop stresses are calculated for design internal pressure using the finite element model in the manner described above. The hoop stresses can be evaluated for acceptance by use of paragraph NB-3213.10 of the ASME Code. Figure 2 illustrates the concept of local primary membrane stress which is defined by this paragraph of the Code. From the Code, "a stressed region may be considered local if the distance over which the membrane stress intensity exceeds 1.1S_m does not extend in the meridional direction more than 1.0(R_t)°. For application to locally thinned pipes, the meridional direction is axial to the pipe, and t is t_m. NB-3213.10 also sets a limit on the proximity of areas where membrane stresses can be considered as local. "Regions of local

2.2 Primary stress intensity involving axisymmetric membrane stress distributions which exceed 1.1S_m shall not be closer in the meridional direction than 2.5(R_t)°. If both of these conditions are met by the hoop stress distribution calculated by the finite element analysis, then the allowable stress of 1.5S_m defined in Figure NB-3221-1 of the ASME Code for local membrane stresses can be used to qualify the hoop stresses resulting from design pressure.

2.3 Axial stresses due to design conditions are checked by equation (9) of NB-3652 of the ASME Code (see Attachment VII). The PD_/2t portion of the first term in this equation is replaced by the maximum axial stress in the locally thinned area calculated by the finite element model for the second load case described above. The D_M_/2t portion of the second term is replaced by the maximum axial stress obtained from the finite element model for the third load case. The finite element stresses implicitly include stress concentration effects, and stress intensification terms in the Code equations should be set to unity, i.e., the finite element stresses should not be modified by a stress intensification factor. If the limitations of equation (9) of NB-3652 are met, the axial stresses in the locally thinned area meet the Class 1 requirements for design conditions.
2.4 For Service Level A and B conditions, equation (10) of NB-3653 must be met. This equation includes the temperature ranges $T_a - T_b$ and $\Delta T_1$. These terms can be taken from the original piping evaluation. The smaller thickness will result in smaller temperature gradient across the thickness, and therefore, it is conservative to use the $\Delta T_1$ from the original piping evaluation. The thinning also decreases the stiffness of the pipe which makes it conservative to use the $T_a - T_b$ terms from the original analysis. In general, it is not expected that local thinning will have a significant effect on the $\Delta T_1$ and $T_a - T_b$ stresses. The first two terms are evaluated in the same manner as in equation (9), with the exception that operating pressure and moment ranges resulting from the Service Level A and B loading conditions are substituted in the pressure and bending moment terms.

2.5 If the Service Level A and B stress requirements are met, the Class 1 fatigue requirements for cyclic operation must also be checked. The basis of this fatigue evaluation for Class 1 piping is Code equation (11) of NB-3653. The additional through-wall thermal term corresponding to $\Delta T_2$ should be taken from the original piping evaluation, since the thinned pipe will have actual $\Delta T_2 < \Delta T_2$ of the original $\Delta T_2$. The pressure and $M$ terms from Code equation (10) are the same except they are multiplied by $K_1$ and $K_2$, respectively, in Code equation (11). The $K_1$ and $K_2$ terms are used to multiply the finite element stresses if the model is not expected to include all necessary details (stress concentrations at butt weld). For a very refined model that is expected to accurately model all stress concentration effects, it may be justified to set $K_1 = K_2 = 1.0$. The remainder of the fatigue evaluation is the same as in the original piping evaluation.

3.0 Evaluation Procedure for Non-Class 1 Piping

3.1 For ASME Class 2 and 3 piping, and ANSI B31.1 piping, hoop stresses calculated by the finite element model may be evaluated using the same method as described above, except the allowable stress for local membrane stresses is taken as 1.5S instead of 1.5$S_m$. For the axial stresses due to internal pressure and primary bending moments, the $P_d/4t_m$, $M_a/Z$ and $(M_a + M_d)/Z$ terms in the Code of Construction piping equations are replaced with the corresponding results from the finite element analysis. The finite element stresses implicitly include stress concentration effects, and stress intensification terms in the Code equations should be set to unity, i.e., the finite element stresses should not be modified by a stress intensification factor. Axial stresses due to secondary loadings (thermal expansion, thermal anchor movement and seismic anchor movement) are checked for compliance with the original Code of Construction by substituting the appropriate results from the finite element analysis into the $M_c/Z$ term in the Code equations for thermal expansion.

3.2 To determine if an evaluation for cyclic operation is necessary, use the criteria described in Section 3.7 of Attachment IX.
Finite Element Analysis Methods

Develop Finite Element Model

Mechanical and Thermal Bending Moments → Calculate Maximum Hoop and Axial Stresses in Locally Thinned Area → Internal Pressure

Class 1 Piping?

Yes

Design Condition Stress Requirements Met?

Yes

Obtain Through-Wall Thermal Stresses from Original Piping Evaluation

Service Level A & B Stress Requirements Met?

Yes

Are Requirements for Cyclic Operation Met?

Yes

Code Repair or Replacement

No

Monitor

No

Are Requirements for Cyclic Operation Required?

Yes

Are Requirements for Secondary Stresses Met?

Yes

Evaluation for Cyclic Operation Required?

Yes

Are Requirements for Primary Stresses Met?

Yes

No

Figure 1: Finite Element Analysis Method
Attachment 7.9: Informational Attachment
Attachment X: Pipe Wall Thinning Evaluation: Finite Element Analysis Methods

Figure 2: Illustration of Local Primary Membrane Stress

\[ \sigma = 2.5\sqrt{R_{t_1}} \]

\[ L_{\text{avg}} = \frac{(L_{m1} + L_{m2})}{2} \]

\[ L_{\text{mm}} = \text{Larger of } L_{m1}, L_{m2} \]
1.0 INTRODUCTION

1.1 This attachment utilizes later editions of the Section XI Codes, as detailed below, which may not be addressed in the Codes referenced by Table 6 in Attachment III. Approval from the plant licensing department, and/or NRC, may be required prior to utilizing the provisions of this attachment.

1.1.1 Tables 3 and 4 may not be addressed in the Codes referenced by Table 6 in Attachment III for ANO-1 (ISI), GGNS, RBS and W3.

1.2 Flaw indications in piping which are characterized as cracklike should be evaluated in accordance with ASME Section XI. The steps in the process include:

1.2.1 Flaw characterization and sizing to determine its length and depth in accordance with ASME Section XI Article IWA-3300.

1.2.2 Comparison of the flaw dimensions to the appropriate acceptance standards of Section XI Articles IWB-3500, IWC-3000, or IWD-3000 as appropriate.

1.2.3 Analytical evaluation for flaws which exceed the acceptance standards.

1.2.4 This attachment provides a detailed standard for characterizing cracklike flaws in Entergy nuclear plant piping and for determining their acceptability in accordance with ASME Section XI acceptance standards. Analytical evaluation procedures for flaws which exceed the standards are provided in Attachments XII through XV. The technical basis for the standards is documented in Reference A.18 of Attachment I.

2.0 FLAW CHARACTERIZATION AND SIZING

2.0.1 Cracklike flaws should first be characterized as planar, laminar, or linear flaws, in accordance with the following definitions.

2.0.2 Planar flaws are flaws which are cracklike in nature and oriented, at least partly, in the through-wall direction of the pipe. They are planar in nature, possessing only two dimensions, length and depth, and the depth dimension has a significant component which is perpendicular to the inside or outside surfaces of the pipe (see figure 1).
2.02.1 Planar flaw indications are further characterized as surface or subsurface flaws depending upon their proximity to the nearest surface of the pipe. Flaws which intersect the surface, or are within a prescribed distance "S" from the surface are classified as surface flaws, see figures 1 and 2. All other planar flaws are considered subsurface flaws. Non-cracklike flaws, such as weld porosity or slag, which are volumetric in nature (possess three dimensions), may be conservatively assumed to be planar flaws for purposes of evaluation. In this case, the minimum of the three directions is ignored, and the other two dimensions are assigned as the flaw length and depth, in accordance with the planar flaw sizing rules. The ultrasonic examination techniques used for in-service inspections are in general incapable of distinguishing between volumetric and planar defects, so this assumption is a common one.

2.03 Laminar flaws are similar to planar flaws, but are oriented in a plane that is essentially parallel (within 10°) to the inside or outside surface of the pipe (see figure 6).

2.04 Linear flaws are planar flaws which have been detected by radiography (RT) or surface examination (PT or MT), such that the depth dimension has not been measured and only the length dimension is known.

2.05 The basic flaw sizing approach consists of bounding the observed flaw with a rectangle that fully contains the area of the flaw, as illustrated in Figure 1. The length of the flaw "l" corresponds to the length dimension of the rectangle, which is parallel to the surface of the pipe. The depth dimension corresponds to the through-wall component of the rectangle, which is perpendicular to the surface of the pipe. For surface flaws, the depth of the rectangle is denoted "a", while for subsurface flaws, the through-wall depth is denoted "2a" (see Figure 1). The "a" and "l" dimensions are assumed to correspond to the minor half-axis and major axis of an ellipse for purposes of fracture mechanics analysis. Special rules are provided for determining "a" and "l" in the case of multiple flaws, flaws which are close to the pipe surface, or flaws oriented in curved or parallel planes. These are described in the following paragraphs.

2.1 Surface Flaw Proximity Rules

2.1.1 Characterization of planar flaws which are close to the surface of a component, but do not intersect the surface is illustrated in Figure 2. In this case, the non-destructive examination technique is used to determine the minimum separation distance "S" from the surface to the closest point of the flaw. The through-wall depth of the flaw is then determined, which is temporarily denoted "2d". If S is greater than or equal to 0.4d, then the flaw is a subsurface flaw, and the characteristic flaw depth a is set equal to d. If S is less than 0.4d, then the flaw must be assumed to be a surface flaw, and the uncracked ligament S is added to the crack depth to create a total surface flaw depth a = 2d + S. Note that for cases in which the uncracked ligament S is between 0.4d and d, the flaw is classified as subsurface, but there is an adjustment to the subsurface flaw acceptance standards using a "Y" factor as described in section 3.1.

2.1.2 In the case of clad piping, proximity to the clad surface is determined assuming the clad-base metal interface to be the inside surface of the pipe. The location of the clad-base metal interface may be determined by non-destructive testing, or estimated from design drawings.
2.2 Multiple Flaw Proximity Rules

2.2.1 Characterization of multiple, closely-spaced planar flaws is also performed using proximity rules, as illustrated in Figure 3. Each individual flaw is characterized in terms of a through-wall depth dimension $d_i$, ($i=1,2,\ldots,n$, where $n$ is the total number of flaws). The largest characteristic depth is used as the basis for the proximity rules. If the spacing between the flaws, $S$, is less than twice the largest characteristic depth, $2d_{\text{max}}$, either in the length or depth direction, then the flaws must be combined into a single planar flaw with length and depth equal to the complete flawed area, as illustrated in the figure. If the flaw spacing is greater than $2d_{\text{max}}$, then each flaw may be individually sized with its own length and depth dimension, and evaluated separately.

2.3 Skewed or Non-planar Flaws

2.3.1 Flaws which are not oriented perpendicular to one of the principal stress directions (axial or hoop) may be evaluated based on their projected areas ($l$ and $a$ dimensions) in the principal stress plane closest to the actual plane of the flaw. This rule also applies to flaws in a curved or non-planar surface (Figure 4).

2.4 Flaws in Multiple Planes (see IWA-3300)

2.4.1 Proximity rules for flaws in multiple planes are illustrated in Figures 5 and 6. For planar flaws, the multiple flaw proximity rules must be applied for combining flaws if the two planes are within a 1/2 inch spacing of one another at the flaw locations (Figure 5). If the spacing of the planes is greater than 1/2 inch, the flaws do not need to be combined.

2.4.2 For laminar oriented flaws (i.e., within 10° of parallel to the pipe surface), flaws in any plane between the front and back surface must be combined if their projections are within a 1 inch spacing (Figure 6).
3.0 FLAW ACCEPTANCE STANDARDS

3.0.1 Acceptance of flaws in piping is governed by ASME Section XI Paragraph IWB-3514 for Class 1 piping, IWC-3514 for Class 2 piping and IWD-3000 for Class 3 piping. At the present time, however, Section XI states that the Class 2 and Class 3 Standards are "in the course of preparation, and that the Standards of IWB-3514 may be applied to these classes of piping."

3.1 Acceptance of Planar Flaws

3.1.1 The ASME Section XI acceptance standards for planar flaws detected during in-service inspection are reproduced in Table 1 and 2, and are illustrated graphically in Figures 7 and 8. Table 1 and Figure 7 apply to ferritic steel piping with a specified minimum yield strength of 50 ksi or less, and which met the ASME Section III minimum fracture toughness requirements of NB-2300, NC-2300, or ND-2300, as applicable. Table 2 and Figure 8 apply to austenitic steel piping with a specified minimum yield strength of 35 ksi or less. Standards are not provided for other piping materials or for materials which do not satisfy these restrictions. In such cases, component specific standards must be developed, or the evaluator must proceed directly to analytical evaluation as described in Attachments XII and XIII. Dissimilar metal welds, such as nozzle safe-ends, are governed by the appropriate piping standards for the side of the weld being evaluated. Flaws in the carbon or low-alloy steel side of a dissimilar metal weld are evaluated by the ferritic steel standards, and flaws on the high alloy steel side, including the weld metal (typically) are evaluated by the austenitic steel standards.

3.1.2 The standards consist of allowable values of normalized flaw depth (a/t) in percent, versus flaw aspect ratio (a/l), where a and l are the flaw depth and length, determined in accordance with the rules of section 2.0, and t is the piping wall thickness at the location of the observed flaw. The piping wall thickness may be determined by non-destructive testing or estimated from design drawings. Separate columns of allowable flaw depth are provided for different piping wall thicknesses, and for surface and subsurface flaws. For near-surface flaws, the subsurface flaw allowables are modified with a Y factor.

3.1.3 Application of the standards is straightforward. Simply compute a/t and a/l for the observed flaw, and compare it to the appropriate column in the tables (or curve in the figures). If the pipe wall thickness or flaw aspect ratio falls between any of the specified values, interpolation is permitted. If the flaw is a subsurface flaw, with distance, S, from the nearest surface in the range of 0.4a ≤ S ≤ a, then multiply the allowable flaw depth by the ratio Y = S/a. For S < 0.4a the flaw is classified as a surface flaw, and a new a is defined as described in section 2.1 and Figure 2. If S > a, set Y = 1.0.

3.1.4 Example applications of the acceptance standards to some typical piping problems are discussed in section 3.4.

3.2 Acceptance of Laminar Flaw

3.2.1 Acceptance standards for laminar flaw indications (laminations) are governed by a single set of standards for both types of material. These standards are presented in Table 3, and consist of allowable lamination areas as a function of pipe wall thickness. The areas are determined in accordance with the characterization rules of section 2.0 above. Once again, interpolation is permitted for intermediate pipe thicknesses.
3.3 Acceptance of Linear Flaws

3.3.1 Acceptance standards for linear flaws in ferritic and austenitic steel piping are presented in Table 4. These are presented in the form of allowable lengths for various pipe wall thicknesses. These are further broken down into allowable lengths of surface flaws (typically from surface examinations such as PT or MT), and allowable lengths for subsurface flaws (typically from radiography, RT, by which method depth generally is unavailable). The linear flaw acceptance standards are generally more conservative than the planar flaw acceptance standards described in section 3.1, because of the uncertainty of the depth dimension. An acceptable option, for flaws which fail to meet these standards, is to perform augmented inspections (typically UT), to define both the length and depth of the observed indication, following which the flaw can be evaluated by the planar flaw standards.

3.4 Example applications

3.4.1 Figure 9 illustrates two typical subsurface flaw indications in a nominally 1-inch thick, carbon steel pipe weld. Flaw A is a typical subsurface flaw, located along a weld fusion line essentially at the mid-wall of the pipe. It is 0.5 inches long, circumferentially oriented, and has a through-wall depth of 0.14 inches. Evaluation of this flaw in accordance with the acceptance standards is illustrated by the calculations in the lower portion of the figure. Since it is a subsurface flaw, the total through-wall depth is denoted "2a", and the flaw depth dimension to be used for evaluation purposes is one-half this value, or 0.07 inches. The normalized flaw evaluation parameters are a/t = 0.14 and a/t = 0.07. Referring to the 1-inch wall thickness subsurface flaw column of Table 1, and interpolating for the aspect ratio of 0.14 (between 0.10 and 0.15), the allowable flaw depth is 15.4% or 0.154. Note that the Y factor is set equal to 1.0 in this case, since the flaw is well removed from the surface (S/a >> 1). Therefore, flaw A is acceptable by a comfortable margin (a/t of 0.07 versus an allowable of 0.154).

3.4.2 Flaw B (Figure 9) is located fairly close to the surface of the pipe, such that application of the surface proximity rule is required. This flaw is 2.7 inches long, with a through wall dimension of 0.1 inches, but is located 0.03 inches from the inside surface of the pipe. The through-wall dimension is temporarily denoted "2d" (since we are not yet sure whether this will be the depth used for evaluation). S/d is thus equal to 0.6, from which we conclude that the flaw may be evaluated as a subsurface flaw, but that the standards must be adjusted via a Y-factor. Since the flaw is subsurface, "a" may be set equal to d, or 0.05 inches, from which the flaw evaluation parameters are a/t = 0.019 and a/t = 0.05. Again referring to the 1-inch wall thickness, subsurface flaw column of Table 1, and interpolating for a/t = 0.019 (between 0.00 and 0.05) yields an allowable flaw depth of 12.75%, which must be multiplied by Y of 0.6. Thus the actual allowable flaw depth is 7.6% or 0.076, and the observed flaw, with a/t of 0.05 is acceptable. Note however, that the combined effects of surface proximity and the longer flaw length considerably reduced the allowable flaw size relative to Flaw A.
3.4.3 Figure 10 illustrates a pair of near-surface indications (Flaw C) in a 1.75 inch thick stainless steel pipe, which are close enough to the surface and to each other to require checking in accordance with the proximity rules of sections 2.1 and 2.2. To provide a basis for comparison, the two individual flaws are sized exactly the same as Flaws A and B of Figure 9, but they have been placed closer together, with only a 0.02 inch spacing between the flaws. The near surface flaw is also 0.03 inches from the surface, identical to Flaw B. Denoting the two flaw depth dimensions, $d_1 = 0.07$ inches and $d_2 = 0.05$ inches, the proximity rules require the two flaws to be combined, since the 0.02 inch spacing is less than 2$d$. Thus the combined depth, 2$d$, is the sum of the two flaw depths plus the spacing, or 0.26 inches, and the flaw length is the combined length of 3.2 inches. Next the surface flaw proximity must be checked. $S/d = 0.231$ which is less than 0.4, so that Flaw C must be treated as a surface flaw.

3.4.4 As a surface flaw, the flaw evaluation depth "a" is the total through-wall dimension, 0.26 inches, plus the surface spacing dimension 0.03 inches, or 0.29 inches. The flaw evaluation parameters are thus $a/l = 0.091$, and $a/t = 0.166$. Referring to Table 2 for austenitic steel piping, and interpolating both for the 1.75 inch thickness (between 1-inch and 2-inch) and for the 0.091 aspect ratio (between 0.05 and 0.10), yields an allowable surface flaw depth of $a_{allow} = 0.105$. Thus Flaw C is unacceptable, and detailed fracture mechanics evaluation or repair is required. This example illustrates the importance of multiple flaw and surface proximity rules. Two flaws which were acceptable by comfortable margins (in a 1-inch thick pipe), became unacceptable (even in a 1.75-inch thick pipe) when they were moved close enough together that they had to be combined, and thus became close enough to the surface that they had to be treated as surface flaw.

3.4.5 Figure 10 also illustrates a lamination in the base metal adjacent to the weld, Flaw D, which must be evaluated in accordance with the laminar flaw standards. The total cross-sectional area of this lamination, assuming it to be rectangular, is 3 in$^2$. Referring to Table 3, for a 1.75-inch thick pipe (between 0.625-inch and 3.5-inch), the allowable lamination area is 7.5 in$^2$, (using ref. A.37), so the lamination is acceptable.

3.4.6 As a final example, it is instructive to assume that Flaws A, B, and C were detected by radiography, and that depth information is therefore unavailable. The flaws must thus be evaluated using the linear flaw acceptance standards of Table 4. Referring to these tables, Flaw A for 1" pipe thickness, is unacceptable (0.5-inch length versus an allowable of 3/8-inch), flaw B is unacceptable (2.7-inch length versus an allowable of 3/8-inch), and for 1.75" pipe wall thickness Flaw C is also unacceptable (3.2-inch length, versus an interpolated allowable of 0.656-inch). This example illustrates the advantage of performing supplemental examinations to define flaw depth in the case of unacceptable linear indications. Two of the three indications were acceptable when the depth dimensions were defined.
### TABLE 1: ASME Section XI Allowable Flaw Size Standards (a/t %) Planar Flaws in Ferritic Steel Piping (with minimum yield strength of 50 ksi or less at 100°F)

<table>
<thead>
<tr>
<th>a/l</th>
<th>t = 0.312 in.</th>
<th>t = 1.0 in.</th>
<th>t = 2.0 in.</th>
<th>t = 3.0 in.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>surface</td>
<td>subsurf.</td>
<td>surface</td>
<td>subsurf.</td>
</tr>
<tr>
<td>0.00</td>
<td>11.1</td>
<td>13.8Y</td>
<td>10.0</td>
<td>12.6Y</td>
</tr>
<tr>
<td>0.05</td>
<td>11.8</td>
<td>14.4Y</td>
<td>10.8</td>
<td>13.0Y</td>
</tr>
<tr>
<td>0.10</td>
<td>13.0</td>
<td>15.6Y</td>
<td>11.8</td>
<td>14.2Y</td>
</tr>
<tr>
<td>0.15</td>
<td>14.4</td>
<td>17.2Y</td>
<td>13.2</td>
<td>15.7Y</td>
</tr>
<tr>
<td>0.20</td>
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<td>17.2Y</td>
<td>14.8</td>
<td>17.7Y</td>
</tr>
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<td>17.2Y</td>
<td>14.8</td>
<td>17.7Y</td>
</tr>
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<td>14.4</td>
<td>17.2Y</td>
<td>14.8</td>
<td>17.7Y</td>
</tr>
</tbody>
</table>

**Notes:** Y = s/a. If S < 0.4d, the flaw is classified as a surface flaw. If Y > 1.0, use Y = 1.0.

**Source:** Inservice Inspection - Table IWB-3514- 2 [A.11] and Table IWB-3514- 1 [A.10]
### TABLE 2: ASME Section XI Allowable Flaw Size Standards (a/t %) Planar Flaws in Austenitic Steel Piping (with minimum yield strength of 35 ksi or less at 1000 F)

<table>
<thead>
<tr>
<th>a/t</th>
<th>t = 0.312 in.</th>
<th>t = 1.0 in.</th>
<th>t = 2.0 in.</th>
<th>t = 3.0 in.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>surface</td>
<td>subsurf.</td>
<td>surface</td>
<td>subsurf.</td>
</tr>
<tr>
<td>0.00</td>
<td>11.7</td>
<td>11.7Y</td>
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<td>12.0Y</td>
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</tr>
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</tr>
<tr>
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<td>11.1Y</td>
</tr>
<tr>
<td>0.20</td>
<td>12.5</td>
<td>12.5Y</td>
<td>11.4</td>
<td>11.4Y</td>
</tr>
<tr>
<td>0.25</td>
<td>12.5</td>
<td>12.5Y</td>
<td>11.5</td>
<td>11.5Y</td>
</tr>
<tr>
<td>0.30</td>
<td>12.5</td>
<td>12.5Y</td>
<td>11.7</td>
<td>11.7Y</td>
</tr>
<tr>
<td>0.35</td>
<td>12.5</td>
<td>12.5Y</td>
<td>11.9</td>
<td>11.9Y</td>
</tr>
<tr>
<td>0.40</td>
<td>12.5</td>
<td>12.5Y</td>
<td>12.1</td>
<td>12.1Y</td>
</tr>
<tr>
<td>0.45</td>
<td>12.5</td>
<td>12.5Y</td>
<td>12.2</td>
<td>12.2Y</td>
</tr>
<tr>
<td>0.50</td>
<td>12.5</td>
<td>12.5Y</td>
<td>12.5</td>
<td>12.5Y</td>
</tr>
</tbody>
</table>

**Notes:** Y = s/a. If S < 0.4d, the flaw is classified as a surface flaw. If Y > 1.0, use Y = 1.0.

**Source:** Inservice Inspection - Table IWB-3514-2[A.10] and Table IWB-3514-3[A.11].
### TABLE 3: ASME Section XI Allowable Flaw Size Standards Laminar Flaws in Piping (Allowable Areas, sq.in.)

<table>
<thead>
<tr>
<th>Nominal Pipe Wall Thickness</th>
<th>Laminar Area sq.in.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.625 in. &amp; less</td>
<td>1.25 (7.5&quot;)</td>
</tr>
<tr>
<td>2.0 in. (3.5&quot;) *</td>
<td>4.0 (7.5&quot;)</td>
</tr>
<tr>
<td>6.0 in.</td>
<td>12.0</td>
</tr>
</tbody>
</table>

**Notes:** Linear interpolation with respect to nominal pipe wall thickness is permissible to determine value of allowable laminar area; see IWA-3200(c).

**Source:** Table IWB-3514-6 [A.11] and Table IWB-3514-3 [A.10]

* Since References A.10 and A.11 provide conservative values in lieu Reference A. 37, Table IWB-3514.3 can be used.

### TABLE 4: ASME Section XI Allowable Flaw Size Standards Linear Flaws in Piping (Allowable Lengths, in.)

<table>
<thead>
<tr>
<th>Nominal Pipe Wall Thickness</th>
<th>Ferritic Steel¹</th>
<th>Austenitic Steel²</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.312 in.</td>
<td>0.1875</td>
<td>0.25</td>
</tr>
<tr>
<td>1.0 in.</td>
<td>0.3125</td>
<td>0.375</td>
</tr>
<tr>
<td>2.0 in.</td>
<td>0.625</td>
<td>0.75</td>
</tr>
<tr>
<td>3.0 in.</td>
<td>0.875</td>
<td>1.2</td>
</tr>
<tr>
<td>4.0 in.</td>
<td>0.875</td>
<td>1.4</td>
</tr>
</tbody>
</table>

**Notes:** For intermediate values of nominal pipe wall thickness, interpolation with respect to linear interpolation is permissible, see IWA-3200(c).

**Source:**
1. Table IWB-3514-4 [A.10], (Applicable to Ferritic steels with yield strength of 50 ksi or less at 100°F)
2. For Austenitic steels in the absence of allowable flaw size standards for linear flaws standards use allowable flaw size standards for allowable planar flaws. References A.10: Table IWB-3614-2. Also, in the absence of information of subsurface flaws conservatively use same as ferritic steels.
Figure 1  Basic Flaw Sizing Method from
ASME Section XI

Source: Ref. A.10 and A.11, Fig. IWA-3310-1.
If $S \geq 0.4d$, Flaw is subsurface, $a = d$

If $S < 0.4d$, Flaw is surface, $a = 2d + S$

Clad Surface

Pressure retaining surface of unclad component or clad-base metal interface of clad component

**Figure 2** Near-Surface Flaw Proximity Rule from ASME Section XI

Source: Ref. A.10 and A.11, Fig IWA-3310-1 and IWA-3320-1.
Figure 3 Flaw-to-Flaw Proximity Rule from ASME Section XI

Source: Ref. A.10 and A.11, Figure IWA-3330-1.
GENERAL NOTE:
Flaw area shall be projected in planes normal to principal stresses $\sigma_1$ and $\sigma_2$ to determine critical orientation for comparison with allowable indication standards.

Figure 4: Flaw Sizing Method for Skewed or Non-Planar Flaws from ASME Section XI

Source: Ref. A.10 and A.11, Fig. IWA-3340-1.
Attachment 7.9: Informational Attachment

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**Figure 5:** Flaw Sizing Rules for Planar Flaws in Multiple Planes

Source: Ref. A.10 and A.11, Fig. IWA-3350-1.
Figure 6: Flaw Sizing Rules for Laminar Flaws in Multiple Planes

Source: Ref. A.10 and A.11, Fig. IWA-3360-1.
Surface Flaws

Figure 7A  Ferritic Flaw Standards

Source: See Table 1
Reference: A.10 and A.11, Table IWB-3514-1, Inservice Inspection.
Subsurface Flaws

![Graph showing subsurface flaws](image)

**Figure 7B  Ferritic Flaw Standards**

Source: See Table 1
Reference: Inservice Inspection - Table IWB-3514-1 [A.10] and Table IWB-3514-2 [A.11].
Surface & Subsurface Flaws

![Figure 8: Austenitic Flaw Standards]

Source: See Table 2
Reference: Inservice Inspection - Table IWB-3514-2 [A.10] and Table IWB-3514-3 [A.11].
Flaw A (Subsurface)

\[ \begin{align*}
2a &= 0.14" \\
a &= 0.07" \\
l &= 0.5" \\
a/l &= 0.14" \\
a/t &= 0.07 \\
\text{Allowable } a/t &= 0.154 \\
(\text{see table 1}) \\
\text{Flaw is acceptable}
\end{align*} \]

Flaw B (Subsurface)

\[ \begin{align*}
2d &= 0.1" \\
d &= 0.05"; \quad 0.4d &= 0.02" \\
S &= 0.03" \\
.4d &> S < d; \quad \triangleleft \text{ Subsurface Flaw; } \triangleright d = a; \\
\triangledown a &= 0.05" \\
\triangledown \text{ Subsurface Flaw } S/a &= 0.6 = Y \\
t &= 1" \\
a/l &= 0.019 \\
a/t &= 0.05 \\
\text{Allowable } a/l &= 0.127Y = 0.076 \\
(\text{see table 1}) \\
\text{Flaw is acceptable}
\end{align*} \]

Figure 9: Subsurface Flaw Evaluation Examples
Figure 10: Surface and Laminar Flaw Evaluation Examples
1.0 INTRODUCTION

1.1 This attachment utilizes the 1989 Edition of the Section XI Code which is not addressed in the Codes referenced by Table 6 in Attachment III. Approval from the plant licensing department, and/or NRC, may be required prior to utilizing the provisions of this attachment.

1.2 This attachment provides for evaluations of crack-like flaws in austenitic steels, a formalized approach to explain the terminology and salient equations in select references available for such evaluations. A case by case approach and appropriate methodology has to be selected to solve an individual problem. Since most of the problems involving crack-like flaw evaluations in stainless steel are of an extremely complex nature, it is not recommended to select any approach without first understanding the root cause and nature of the crack-like flaw. For example inter-granular stress corrosion cracking (IGSCC) is a phenomenon most common to crack-like flaws occurring in austenitic steel, and considering the complexities of this phenomenon this has been excluded from the scope of this attachment except for occasional references to this phenomenon. Thus, this attachment should be used as an introductory material and needs to be supplemented from other sources. This attachment can be used after it has been determined that the Code approaches discussed in this attachment are appropriate for any particular problem.

1.3 The procedure for evaluation of flaws in austenitic stainless steel piping material is provided in Subsection IWB-3640 and Appendix C of the ASME Code, Section XI [A.37] for Class 1 piping. Currently, there are no evaluation procedures in the Code for Class 2 and 3 piping, so the procedure for Class 1 is generally applied to Class 2 and 3 piping systems. The procedure is summarized in the flow chart presented in Figure 1. The technical basis for the evaluation procedure is provided in Reference A.19.

1.4 Austenitic stainless steel piping material can be classified into two basic groups. The first group consists of wrought product and non-flux welds. Experimental studies have shown that these materials have adequate toughness such that in the presence of a flaw they fail by net section collapse (limit load) when subjected to piping loads. The second group consists of the flux weldments (shielded metal arc weldments (SMAW) and submerged arc weldments (SAW). Experimental studies have shown that materials in this group have lower toughness compared to the wrought material and the non-flux welds. These materials fail by unstable ductile tearing prior to reaching limit load. Because of this, allowable flaw sizes for flux welds were developed from elastic-plastic fracture mechanics using the J-integral and ductile tearing modulus instability criterion.

1.5 It is to be noted that as indicated in the flow chart for evaluation of crack-like flaws. Figure 7.3 of this DEAM, if evaluation methods using IWB-3600 (Class 1) or IWC 3600 (Class 2) and IWD 3600 (Class 3) are used, a prompt reporting has to be submitted for regulatory concurrence. The system, however can be operable until the regulatory approval.
The evaluation procedures in this attachment are applicable to pipes NPS 4 in. or greater. In general, crack-like defects are found in welds and the adjacent discontinuities or heat-affected zones. The evaluation procedures are applicable to a distance of \( \sqrt{R_0 t} \) from the centerline of a girth butt weld, where \( R_0 \) is the nominal outside radius and \( t \) is the nominal pipe wall thickness. Components / fittings outside these limitations should be treated on a case-by-case basis.

2.0 STRESSES

2.1 Stresses are provided separately for allowable flaw size determination and flaw growth analysis. For allowable flaw size determination (section 2.2) primary stresses are considered, and in some cases secondary stresses may be considered. For flaw growth analysis (section 2.3) secondary stresses are considered in addition to the piping and expansion stresses.

2.2 Stresses for Allowable Flaw Size Determination

2.2.1 In the evaluation of flaw in austenitic piping, three classes of stresses are required:

2.2.1.1 Primary membrane stress \( (P_m) \)

2.2.1.2 Primary bending stress \( (P_b) \)

2.2.1.3 Thermal expansion stress \( (P_e) \)

2.2.2 These stresses can be obtained from the piping stress report. \( P_m \) is associated with pressure stress, \( P_b \) is generally associated with dead weight and seismic loads, and \( P_e \) is restraint stresses arising from thermal expansion.

2.2.3 The above \( P_m \) and \( P_b \) stresses correspond to un-concentrated (without stress intensification factors) primary stress intensity values defined in Equation 9 of ASME Section III NB-3650. \( P_e \) is un-concentrated stress intensity value for moment loads defined in Equation 10 of ASME Section III, NB-3650.

2.3 Stresses and Flaw Growth

2.3.1 It is important to determine the loads that contribute to the flaw growth.

2.3.1.1 For fatigue, both the magnitude of the stress and cyclic information should be obtained from the stress report or any supplementary evaluation that may have been performed as part of the root cause evaluation.

2.3.1.2 For IGSCC evaluation, the sustained stress which contributes to SCC must be considered. The sustained stresses consist of \( P_m \) \( P_b \) and \( P_e \) from section 2.2 above and weld residual stresses, when applicable.
2.3.2 Butt weld residual stresses play a major role in flaw growth evaluation. A through-wall butt welding residual stress profile has been provided in NUREG-0313 [A.20] and shown in Figure 2. This residual stress profile is appropriate for large diameter piping (thickness greater than 1.0 inch) and is consistent with note 3 of the figure. For small diameter piping, linear through-wall bending residual stress distribution provided in Reference A.19 and NUREG-1061 [A.21] is recommended.

3.0 LOAD COMBINATION

3.1 For allowable flaw size determination, two load combinations are considered in ASME Section XI [A.37]

3.1.1 Normal operating (including Upset and Test)  Level A/B

3.1.2 Emergency / faulted  Level C/D

3.2 The load combinations are generally reported in the piping Stress Report but, in general, the following load combinations are typical.

3.2.1 Level A/B  \( P_m \) - Pressure

\( P_b \) - Deadweight + OBE Seismic

\( P_t \) - Thermal expansion

3.2.2 Level C/D  \( P_m \) - Pressure

\( P_b \) - Deadweight + SSE Seismic

\( P_t \) - Thermal expansion

3.3 For fatigue crack growth analysis, only the cyclic loads in the above load combinations are considered.

3.4 For IGSCC crack growth evaluation, only the sustained stresses are considered. This generally includes a combination of Pressure, Deadweight, Thermal Expansion and Weld Residual Stress.

4.0 Material Properties

4.1 In performing ASME Section XI allowable flaw size evaluation, the important material property is the ASME Section III allowable stress intensity limit, \( S_m \). The value of \( S_m \) for various types of austenitic stainless steel is provided in Table I-1.2 of the ASME Section III appendices, for Class 1 materials [A.38].
4.2 When a J-Integral/ Tearing Modulus analysis is performed for the flux weld, additional material properties are required. These include the Ramberg-Osgood stress-strain curve parameters \( \alpha \) and \( n \), the yield stress \( \sigma_y \), the flow stress \( \sigma_f \), Modulus of Elasticity \( E \), and the fracture toughness \( J_c \). Typical values for SAW and SMAW welds have been provided as follows [A.19]:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Submerged arc weld</th>
<th>Shielded metal arc weld</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha )</td>
<td>11.0</td>
<td>9.0</td>
</tr>
<tr>
<td>( n )</td>
<td>6.9</td>
<td>4.9</td>
</tr>
<tr>
<td>( \sigma_y, \text{ksi} )</td>
<td>33.7</td>
<td>49.4</td>
</tr>
<tr>
<td>( \sigma_f, \text{ksi} )</td>
<td>42.1</td>
<td>55.4</td>
</tr>
<tr>
<td>( E, \text{ksi} )</td>
<td>25,000.0</td>
<td>25,000.0</td>
</tr>
<tr>
<td>( J_c, \text{in-lb/in}^2 )</td>
<td>650.0</td>
<td>990.0</td>
</tr>
</tbody>
</table>

4.3 In addition, the J-T material resistance curve will also be required. Typical curves used in Reference A.19 are shown in Figures 3 and 4.

4.4 The material properties used for flaw growth evaluation are discussed in Section 7.

4.5 Attachment XV, Section 3.0 provides the methodology for performing elastic plastic fracture mechanics (EPFM) analysis using the J-integral / Tearing Modulus Approach.

5.0 Initial Flaw Size and Flaw Orientation

5.1 Initial flaw size and flaw orientation are obtained from ISI reports. Flaws can be either axial or circumferentially oriented. Flaws can also be surface or subsurface. Rules for determining flaw orientation and flaw type are provided in ASME Section XI, IWA-3000.

5.2 In some cases, multiple flaws are encountered. Rules for combining multiple flaws are also provided in IWA-3000. Additional rules for combining multiple IGSCC flaws are provided in NUREG-0313, Rev. 2 [A.20].

6.0 Determination of Stress Intensity Factor (KI) versus Flaw SIZE

6.1 Determine the fracture mechanics model for calculation of stress intensity factor (K) as a function of flaw size. This is determined from the knowledge of the pipe geometry and the flaw orientation. Use of select computer software is pertinent as mentioned in Attachment XIV or methodology provided in Attachment XV.

7.0 Flaw Growth

7.1 The mechanisms for flaw growth should be established from the root cause evaluation. The flaw growth mechanism in austenitic stainless steels could be attributed to either IGSCC or fatigue from cyclic loadings.

7.2 Intergranular Stress Corrosion Cracking (IGSCC)

7.2.1 IGSCC in general occurs in BWR austenitic stainless steel piping.
7.2.2 The procedure for performing IGSCC flaw growth evaluation is beyond the scope of this attachment and thus is excluded due to the extremely complex nature of the flaw growth from IGSCC. The procedure for performing flaw evaluation in BWR austenitic stainless steel piping is provided in NRC documents Generic Letter 88-01 [A.40] and NUREG-0313 Rev. 2 [A.20]. The BWR Vessel and Internals Project is in the process of developing a Topical Report on IGSCC crack growth rate [A.39]. On approval from the USNRC this information will be helpful in developing this subsection.

7.2.3 Other methods consider the environment as well as the material condition of the austenitic stainless steel. A detailed discussion regarding these is beyond the scope of this attachment, but references are provided in A.22 and B.2.

7.3 Fatigue

7.3.1 ASME Code Section XI currently has a fatigue crack growth law for air environment but does not have one for water environment.

7.3.2 The ASME Section XI, Appendix C fatigue crack growth law for air is given as:

$$\frac{da}{dN} = C_a (\Delta K_f)^n$$  \hspace{1cm} \text{Eqn. 2}

where:

$$n = 3.3, \text{ and } C_a = C(S)$$  \hspace{1cm} \text{Eqn. 3}

and C is a scaling parameter to account for temperature, which is given by

$$C = 10^{-10.009 + 8.12 \times 10^{-4} T - 1.13 \times 10^{-6} T^2 + 1.02 \times 10^{-9} T^3}$$  \hspace{1cm} \text{Eqn. 4}

$$\Delta K = K_{\text{max}} - K_{\text{min}}, \text{ ksi } \sqrt{in}$$

7.3.3 $T$ is the metal temperature in °F ($T \leq 800$ °F). $S$ is a scaling parameter to account for the $R$ ratio ($K_{\text{min}} / K_{\text{max}}$), and is given by:

$$S = 1.0 \quad \text{when } R \leq 0$$

$$= 1.0 + 1.8R \quad \text{when } 0 < R \leq 0.79$$

$$= -43.35 + 57.97R \quad \text{when } 0.79 < R < 1.0$$
7.3.4 For water environment, the fatigue crack growth law provided in Reference A.19 can be used. However, due to the complexity of this method it is recommended that all the ramifications are completely understood before this can be applied. This subsection has been provided for information for an understanding of the basic material required in case of any review. This law is based on work sponsored by the Pressure Vessel Research Committee and Metals Properties Council and has the form:

\[ \frac{da}{dN} = C \cdot E \cdot S(\Delta K)^n \]  

Equation 5

where:

- \( da/dN \) = change in crack depth, \( a \), per fatigue cycle, in/cycle
- \( C, n \) = material constants
- \( n = 3.3 \)
- \( C = 2 \times 10^{10} \)
- \( S = R \) ratio correction factor = \([1.0 - 0.5R^2]^{-4}\)
- \( R = \frac{K_{\text{min}}}{K_{\text{max}}} \)
- \( E = \) environmental factor (equal 1.0, 2.0, and 10.0 for air, PWR, and BWR environments, respectively)
- \( \Delta K = K_{\text{max}} - K_{\text{min}} \) ksi(in)
- \( K_{\text{min}}, K_{\text{max}} = \) minimum and maximum values, respectively, of applied stress intensity factor

7.3.5 There are currently efforts in the ASME Code Working Group on Flaw Evaluation to provide an environment fatigue crack growth law for stainless steel.

8.0 Determination of Allowable Flaw Size

8.1 Determination of allowable flaw size for austenitic stainless steel piping is provided in IWB-3640 and Appendix C of Section XI. Allowable flaw sizes for base metal and non-flux welds (GTAW and GMAW) are based on plastic collapse (limit load). Allowable flaw sizes for flux welds (SAW and SMAW) are based on ductile tearing (J-Integral / Tearing Modulus analysis).

8.2 The first step in determining the allowable flaw size is to use the tables provided in IWB-3640. The flow chart (Figure 5) provides guidance for use of these tables. The tables are also summarized below:

8.2.1 IWB-3641-1 - Circumferential Flaws/Normal and Upset
8.2.2 IWB-3641-2 - Circumferential Flaws/Emergency and Faulted
8.2.3 IWB-3641-3 - Axial Flaws/Normal and Upset
8.2.4 IWB-3641-4 - Axial Flaws/Emergency and Faulted
8.2.5 IWB-3641-5 - Circumferential Flaws/Normal and Upset (SMAW/SAW)
8.2.6 IWB-3641-6 - Circumferential Flaws/Emergency and Faulted (SMAW/SAW)

8.3 Table IWB-3641-1

The following are the applicability and assumptions used in developing this table [A.19]. The differences between the base metal, flux and non-flux weld are provided in Section 1.3. Non-fluxed weldments have more toughness than fluxed weldments.

8.3.1 Circ. Flaws - Normal Operating (including Upset and Test) Conditions
8.3.2 For Base Metal and Non-flux GTAW and GMAW Weldments
8.3.3 Based Purely on Plastic Collapse (Limit Load Source Equations)
8.3.4 Only Primary Stresses (No Secondary-Thermal Stresses)
8.3.5 Untensified Stresses
8.3.6 Safety Factor = 2.77
8.3.7 Assumes $\sigma_t = 3S_m$
8.3.8 Assumes $P_m = 0.5S_m$
8.3.9 Maximum Allowable $a/t = 0.75$

8.4 Table IWB-3641-2

8.4.1 Circ. Flaws - Emergency and Faulted Conditions
8.4.2 For Base Metal and Non-flux GTAW and GMAW Weldments
8.4.3 Based Purely on Plastic Collapse (Limit Load Source Equations)
8.4.4 Only Primary Stresses (No Secondary-Thermal Stresses)
8.4.5 Untensified Stresses
8.4.6 Safety Factor = 1.39
8.4.7 Assumes $\sigma_t = 3S_m$
8.4.8 Assumes $P_m = 1.0S_m$

8.4.9 Maximum Allowable $a/t = 0.75$

8.5 Table IWB-3641-3

8.5.1 Axial Flaws - Normal Operating (including Test and Upset) Conditions

8.5.2 For Base Metal and Non-fluxed GTAW and GMAW Weldments

8.5.3 Based on Plastic Collapse

8.5.4 Only Primary Hoop Stress

8.5.5 Unintensified Stresses

8.5.6 Safety Factor = 3.0

8.5.7 $\sigma_t = 3S_m$

8.5.8 Maximum $a/t = 0.75$

8.6 Table IWB-3641-4

8.6.1 Axial Flaws - Emergency and Faulted Conditions

8.6.2 For Base Metal and Non-Flux GTAW and GMAW Weldments

8.6.3 Based on Plastic Collapse

8.6.4 Only Primary Hoop Stresses

8.6.5 Unintensified Stress

8.6.6 Safety Factor = 1.5

8.6.7 $\sigma_t = 3S_m$

8.6.8 Maximum $a/t = 0.75$

8.7 Table IWB-3641-5

8.7.1 Circumferential Flaws - Normal Operating (including Upset and Test) Conditions

8.7.2 For Fluxed SAW and SMAW Weldments

8.7.3 Based on Elastic-Plastic Fracture Mechanics (J/T analysis)
8.7.4 Stress Multipliers Provided to Convert to Equivalent Plastic Collapse Analysis

8.7.5 Both Primary and Secondary Stresses Considered. For non-fluxed welds, only primary stresses are considered.

8.7.6 Safety Factor = 2.77 for Primary Loads

8.7.7 Safety Factor = 1.0 for Thermal Loads

8.7.8 Maximum Allowable a/t = 0.60

8.8 Table IWB-3641-6

8.8.1 Circumferential Flaws - Emergency and Faulted Conditions

8.8.2 For fluxed SAW and SMAW Weldments

8.8.3 Based on Elastic-Plastic Fracture Mechanics (J/T Analysis)

8.8.4 Stress Multipliers Provided to Convert to Equivalent Plastic Collapse analysis

8.8.5 Both Primary and Secondary Stresses Considered. For non-fluxed welds, only primary stresses are considered.

8.8.6 Safety Factor = 1.39 for Primary Loads

8.8.7 Safety Factor = 1.0 for Thermal Loads

8.8.8 Maximum Allowable a/t = 0.60

8.9 The above tables 1 through 6 are the Code allowable tables. No tables are provided in the Code for axial flaws for fluxed weldments.
8.10 When more relief is desired than by using the preceding tables in IWB-3640, the source equations provided in Appendix C of Section XI [A.37] can be used directly. These source equations are based on plastic collapse with adjustments for the flux welds. The stress distribution of a circumferential flawed pipe at plastic collapse is shown in Figure 6. The plastic collapse equations for circumferential flaws are given as:

For $\theta + \beta \leq \pi$

$$P_b = \frac{6S_m}{\pi} \left( 2 \sin \beta - \frac{a}{t} \sin \theta \right)$$

Eqn. 6

$$\beta = \frac{1}{2} \left( \frac{\pi}{t} - \frac{a}{t} - \frac{P_m}{3S_m} \right)$$

Eqn. 7

For $\theta + \beta > \pi$

$$P_b = \frac{6S_m}{\pi} \left( 2 - \frac{a}{t} \right) \sin \beta$$

Eqn. 8

$$\beta = \frac{\pi}{2 - \frac{a}{t}} \left( 1 - \frac{a}{t} - \frac{P_m}{3S_m} \right)$$

Eqn. 9

where all the terms are shown in Figure 6 and

$$\sigma_f = 3S_m$$

Eqn. 10

8.11 For base metal and non-flux welds, the relationship between the failure bending stress $P_b$ and the applied stresses ($P_m$ and $P_b$) is given as:

$$P_b = SF(P_m + P_b + P_e) - P_m$$

Eqn. 11

8.12 For the flux welds (SAW and SMAW weldments), from Appendix C of Section XI [A.37]

$$P_b = Z_1 \cdot SF(P_m + P_b + P_e) - P_m$$

Eqn. 12

$$Z_1 = 1.15 \left[ 1 + 0.013(D - 4) \right] \text{ for SMAW}$$

Eqn. 13

$$= 1.30 \left[ 1 + 0.010(D - 4) \right] \text{ for SAW}$$

where $D$ is the nominal pipe size, NPS and for NPS $\leq 24 \text{ in.}$, use $D = 24$. 
8.13 For axial Part-through Flaws:

$$\sigma_h = \frac{3S_F}{SF} \left[ \frac{t}{a} - 1 \right]$$

Eqn. 14

where:

$$M_2 = \left[ 1 + 1.61 l_f^2 / (4Rt) \right]^{1/2}$$

$$\sigma_h = \text{nominal hoop stress} = PD/2t$$

$$D = \text{nominal outside diameter of the pipe}$$

$$l_f = \text{total flaw length}$$

$$a = \text{flaw depth. The flaw depth is limited to 75\% of thickness}$$

$$R = \text{mean radius of the pipe}$$

$$t = \text{nominal thickness}$$

$$SF = \text{Safety Factor; 3.0 for Level A and B Service Loadings, 1.5 for Level C and D Service Loadings}$$

8.14 The evaluation can also be performed using appropriate computer programs. Alternate methods for plastic collapse which take into account the shape of the flaw and also cases involving multiple flaws are discussed in Attachment XV Section 4.0.
Figure 1: Flaw Evaluation Procedure for Austenitic Steel Piping
Attachment 7.9: Informational Attachment
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<table>
<thead>
<tr>
<th>Wall Thickness</th>
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<tr>
<td></td>
<td>Circumferential (^2)</td>
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<td></td>
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<td>&lt; 1 inch</td>
<td>0 (\text{ID}) - 0.5 (\text{OD})</td>
</tr>
<tr>
<td>(\geq 1) inch</td>
<td>See Note 3</td>
</tr>
<tr>
<td></td>
<td>0 (\text{ID}) - 0.5 (\text{OD})</td>
</tr>
</tbody>
</table>

\(^1\) S = 30 ksi
\(^2\) Considerable variation with weld heat input.
\(^3\) \(\sigma = \sigma_i \left[ 1.0 - 6.91 (a/t) + 8.69 (a/t)^2 - 0.48 (a/t)^3 - 2.03 (a/t)^4 \right] \)
\(\sigma_i = \) stress at inner surface \((a = 0)\)

**Figure 2** Residual Stress Distribution in Large and Small Diameter Piping Welds [A.19, A.21]
Attachment 7.9: Informational Attachment

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Figure 3:  Material J-R Resistance Curve for SAW Weldment at 550°F [A.19]

Figure 4:  Material J-R Resistance Curve for SMAW Weldment at 550°F [A.19]
Figure 5: Flow Chart for Allowable Size Determination of Austenitic Stainless Steel Piping
Figure 6: Stress Distribution in a Cracked Pipe -- Basis for Net Section Collapse Criteria for Austenitic Steel Pipe
1.0 INTRODUCTION

1.1 This attachment utilizes later editions of the Section XI Code which may not be addressed in
the Codes referenced by Table 6 in Attachment III. Approval from the plant licensing
department, and/or NRC, may be required prior to utilizing the pertinent provisions of this
attachment.

1.2 This attachment provides for evaluations of crack-like flaws in ferritic steels, a formalized
approach to explain the terminology, and salient equations in select references available for
such evaluations. A case by case approach and appropriate methodology has to be selected
to solve an individual problem. Since problems involving crack-like flaw evaluations could
be of a complex nature, it is not recommended to select any approach without first understanding
the root cause and nature of the crack-like flaw. Thus, this attachment should be used as an
introductory material and needs to be supplemented from other sources. This attachment can
be used after it has been determined that the Code approaches discussed in this attachment
are appropriate for any particular problem.

1.3 The procedure for evaluation of flaws in Class 1 ferritic piping is provided in Subsection IWB-
3650 and Appendix H of ASME Code Section XI [A.37]. The technical basis for the procedure
is provided in EPRI Report No. NP-6045 [A.13]. The flow chart shown in Figure 1 summarizes
the procedure. There are currently no rules for Class 2 and 3 piping, therefore, the rules of
Class 1 piping are generally used for Class 2 and 3.

1.4 As explained in Reference A.13, the load carrying capacity of flawed ferritic piping can vary
significantly within the LWR operating temperature range. This temperature dependence
results in three distinct regions of fracture behavior, hence each requires a different fracture
mechanics analysis technique.

1.4.1 The “lower shelf” region, where the fracture toughness of the material is a minimum and
does not change significantly with increasing temperature. In this region, the behavior of
the material is generally assumed to be linear elastic because ductility is negligible and
therefore, linear elastic fracture mechanics (LEFM) techniques are applicable.

1.4.2 The “transition temperature” region where the fracture toughness increases significantly
above the lower shelf value with increasing temperature. In this region, elastic-plastic
fracture mechanics (EPFM) techniques involving the use of the J-Integral/Tearing
Modulus analyses are typically employed.

1.4.3 The “upper shelf” region, where the fracture toughness reaches a maximum and ideally
remains constant with increasing temperature. In this region, the material is very ductile
and limit load (net section plastic collapse) analyses are employed in fracture mechanics
evaluation.
1.5 To determine which regions and analyses methods to use, the flow chart shown in Figure 2 is provided in ASME Code, Section XI, Appendix H.

The key to the determination of the analysis method is the determination of a screening criterion (SC). For an explanation of screening criteria see section 2.1.1. Figure 2 indicates that if SC is below 0.2, limit load analysis shall be used. If SC falls between 0.2 and 1.8, elastic-plastic fracture mechanics (EPFM) techniques shall be used. Linear elastic fracture mechanics techniques are used if SC is greater than or equal to 1.8. The computational method for calculating SC is provided in ASME Section XI Appendix H, (ref. A.37).

1.6 The evaluation procedures in this attachment are applicable to pipes NPS 4" or greater. In general, crack-like defects are found in welds and the adjacent discontinuities or heat-affected zones. The evaluation procedures are applicable to a distance of $\sqrt{R_i}$ from the centerline of a girth butt weld, where $R_i$ is the nominal outside radius and $t$ is the nominal pipe wall thickness. Components / fittings outside these limitations should be treated on a case-by-case basis.

2.0 STRESSES

2.1 Screening Criteria and Allowable Flaw Size

2.1.1 Screening criterion (SC) parameter to define the applicable failure mode is [A.37: H-4421 and A.13]:

$$SC = \left[ \frac{K_r'}{S_r} \right]$$

Eqn. 1

where:

$$K_r' = \left[ \frac{K_{r1}}{K_{r2}} \right]$$

Eqn. 2

$$K_{r_e} = \left( J_{r_e} E'/1000 \right)^{1/2} \text{kSI} - \text{in}.$$  

Eqn. 3

$$J_{r_e} = \text{Measure of material toughness due to crack extension at upper shelf, transition, and lower shelf temperatures, } J \text{ integral at first flaw extension, in-lb/in}^3$$

$$E' = \left[ E/(1-v^2) \right] \text{kSI}$$

Eqn. 4

where

$E = \text{Modulus of Elasticity}$

$v = \text{Poisson Ratio}$
$K_t = \text{Total applied stress intensity factor (as defined in sections 7.4.1 and 7.4.2 for circumferential and axial flaws) ksi}^{-\text{\tiny vin}}$

For circumferential flaws, (see section 7.4.1):

$$S'_c = \left[ \frac{\sigma}{\sigma_{b,c}} \right]$$

Eqn. 5

where:

$$\sigma = \sigma_{\text{primary bending}} + \sigma_{\text{expansion}}$$

Eqn. 6a

$$\sigma_{b,c} = \text{bending stress at limit load}$$

Eqn. 6b

For axial flaws, (see section 7.4.2):

$$S'_a = \left[ \frac{\sigma}{\sigma_r} \right]$$

Eqn. 7

where:

$$\sigma = \sigma_{\text{axial stress}}$$

Eqn. 7a

$$\sigma_r = \text{reference stress at limit load}$$

Eqn. 7b

2.1.2 For determination of the screening criterion (SC) and allowable flaw size, three classes of stresses are required:

2.1.2.1 Primary membrane ($P_m$)

2.1.2.2 Primary bending ($P_b$)

2.1.2.3 Thermal expansion ($P_e$)

2.1.3 These stresses are obtained from the piping Stress Report. $P_m$ is associated with pressure stress, $P_b$ is generally associated with dead weight and seismic loads, and $P_e$ is restraint stresses arising from thermal expansion.

2.1.4 The above $P_m$ and $P_b$ stresses correspond to unconcentrated (without stress intensification factors) primary stress intensity values defined in Equation 9 of ASME Section III NB-3650. $P_e$ is unconcentrated stress intensity value for moment loads defined in Equation 12 of ASME Section III, NB-3650.

2.1.5 When LEFM analysis is performed, butt weld residual stresses should also be considered in the determination of allowable flaw size, since these stresses are not expected to relax under LEFM condition. Through-wall butt weld stress distribution for ferritic piping recommended in Reference A.13 is shown in Figure 3.
2.2 Flaw Growth

2.2.1 For ferritic piping, the predominant flaw growth mechanism is fatigue. Ferritic piping is generally immune from intergranular stress corrosion cracking (IGSCC). In flaw growth evaluation, it is important to determine the loads that contribute to the flaw growth. For fatigue, both the magnitude of the stresses and expected number of cycles for all normal and upset operating conditions must be included. This information should be obtained from the stress report or from any supplementary evaluation that may have been performed as part of the root cause evaluation. Butt weld residual stresses should also be considered in the evaluation.

3.0 LOAD COMBINATION

3.1 For allowable flaw size determination, two load combinations are considered in ASME Section XI:

3.1.1 Normal operating (including Upset and Test) Level A/B

3.1.2 Emergency and Faulted Level C/D

3.2 The load combinations are generally reported in the piping Stress Report but, in general, the following load combinations are typical.

3.2.1 Level A/B

<table>
<thead>
<tr>
<th>Value</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>( P_m )</td>
<td>Pressure</td>
</tr>
<tr>
<td>( P_b )</td>
<td>Deadweight + OBE Seismic</td>
</tr>
<tr>
<td>( P_e )</td>
<td>Thermal expansion</td>
</tr>
</tbody>
</table>

3.2.2 Level C/D

<table>
<thead>
<tr>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_m )</td>
<td>Pressure</td>
</tr>
<tr>
<td>( P_b )</td>
<td>Deadweight + SSE Seismic</td>
</tr>
<tr>
<td>( P_e )</td>
<td>Thermal expansion</td>
</tr>
</tbody>
</table>

3.3 For fatigue crack growth analysis, all the cyclic loads which contribute to the crack growth must be considered.

4.0 MATERIAL PROPERTIES

4.1 For the purpose of determining material properties, ferritic piping materials are categorized into two groups in ASME Section XI, Appendix H, also see ref. A.13.

4.1.1 Material Category 1: Seamless or welded wrought carbon steel pipe and pipe fittings that have a specified minimum yield strength not greater than 40 ksi and welds made with E7015, E7016, and E7018 electrodes in the as-welded or post weld heat treated conditions.
4.1.2 Material Category 2: All other ferritic shielded metal arc and submerged arc welds with specified minimum tensile strengths not greater than 80 ksi in the as-welded or post weld heat treated conditions.

4.2 In determining the screening criteria and allowable flaw size, certain material property data is required. This includes:

- Yield Stress, $\sigma_y$
- Ultimate Strength, $\sigma_u$
- Young’s Modulus, $E$
- Poisson Ratio, $\nu$
- Design Stress Intensity, $S_m$
- Fracture Toughness, $J_{ik}$

4.3 The values of $\sigma_y$, $\sigma_u$, $E$, and $S_m$ are provided in Appendix I of ASME Section III [A.38]. The value of $\nu$ is typically taken as 0.3. Minimum values of $J_{ik}$ are provided in ASME Section XI Appendix H if actual values are not available for the evaluation. $J_{ik}$ shall be obtained directly from heat-specific $J_{ik}$ experiments, or correlations with heat-specific Charpy V-notched absorbed energy (CVN) data or reasonable lower bound CVN data.

4.4 The correlation at upper shelf temperatures for use with CVN data for circumferential flaws is given as:

$$J_{1mm} = 10 \text{ CVN}$$

Eqn. 8

where,

- $J_{1mm}$ is flaw extension in in-lb/in$^2$
- CVN is heat specific energy in ft-lb units.

Note that the operating temperature is considered as greater than 200° F. If actual CVN values are available, correlation between fracture toughness and CVN values provided in literature (e.g., ref. A.41) can be used.

4.5 In the absence of specific data, the upper shelf temperature for ferritic piping is specified as 200° F.
4.6 When a J-Integral/Tearing Modulus analysis is performed, additional material properties are required. These include the Ramberg-Osgood stress-strain curve parameters \( \alpha \) and \( n \), and reference stress \( \sigma_r \). Lower bound values for these parameters were determined in Reference A.13 for A106 Gr. B and SA-333-6 materials based on the lower bound stress-strain curve shown in Figure 4.

<table>
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<th>Parameter</th>
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<tr>
<td>( \alpha )</td>
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</tr>
<tr>
<td>( n )</td>
<td>4.2</td>
</tr>
<tr>
<td>( \sigma_r ), ksi</td>
<td>27.1</td>
</tr>
</tbody>
</table>

4.7 In addition, the J-T material resistance curve will also be required. Typical curves used in Reference A.13 are shown in Figures 5 through 8.

5.0 INITIAL FLAW SIZE AND FLAW ORIENTATION

5.1 Initial flaw size and flaw orientation are obtained from ISI reports. Flaws can be either axial or circumferentially oriented. Flaws can also be surface or subsurface. Rules for determining flaw orientation and flaw type are provided in ASME Section XI, IWA-3000. In some cases, multiple flaws are encountered. Rules for combining multiple flaws are also provided in IWA-3000.

6.0 FLAW GROWTH

6.1 The mechanisms for flaw growth should be established from the root cause evaluation. The flaw growth mechanism in ferritic steels is attributed mainly to fatigue. Per Appendix H of Section XI, the fatigue crack growth law for ferritic vessels in Appendix A of Section XI is used. Separate laws are provided for air and water environments. These crack growth laws are included in software programs which address these applications, see attachment XIV.

7.0 DETERMINATION OF ALLOWABLE FLAW SIZE

7.1 The first step in the allowable flaw size determination is to determine the appropriate analysis method for using the screening criteria (SC) provided in Appendix H of ASME Section XI and shown in Figure 2. The screening criteria and the allowable flaw size can be determined using software programs which address these applications, see attachment XIV.

7.2 If SC < 0.2, the limit load analysis technique should be used in determining the allowable flaw size. Flow chart for materials meeting the limit load criteria is provided in Section XI, Appendix H, Article H-5000 and shown in Figure 9. As can be seen from this flow chart, tables are provided in Appendix H as follows:

7.2.1 Table H-5310-1 - Circ. Flaws - Normal/Upset/Test Conditions
7.2.2 Table H-5410-2 - Circ. Flaws - Emergency/Faulted Conditions
7.2.3 Table H-5410-3 - Axial Flaws - Normal/Upset/Test Conditions
7.2.4 Table H-5310-4 - Axial Flaws - Emergency/Faulted Conditions
7.2.5 In lieu of using the above tables, the source equations given in Appendix H may be used. These equations are given as follows:

7.2.5.1 For circumferential flaws [A.37: H-5320]

For $\theta + \beta \leq \pi$

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

Eqn. 9

$$\beta = \frac{1}{2} \left(\pi - \frac{a}{t} \theta - \pi \frac{P_m}{\sigma_f}\right)$$

Eqn. 10

For $\theta + \beta > \pi$

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

Eqn. 11

$$\beta = \frac{\pi}{2 - \frac{a}{t}} \left(1 - \frac{a}{t} - \frac{P_m}{\sigma_f}\right)$$

Eqn. 12

where all the terms are shown in Figure 9 and $\sigma_f$ shall be taken as the average of yield and ultimate stress, or 2.4 $S_m$ when these values are not available.

7.2.5.2 The above formulas are valid for $P_d/P_m \geq 1.0$ and $P_m \leq 0.5 S_m$ for normal operating (including upset and test) conditions or $P_m \leq 1.0 S_m$ for emergency and faulted conditions.

7.2.5.3 The allowable bending stress $S_b$ is given as:

$$S_b = \frac{P_b}{(SF)} - P_m \left[1 - \frac{1}{(SF)}\right]$$

Eqn. 13

where:

$\text{SF} = $ safety factor

$= 2.77$ for normal operating condition

(including upset at test) conditions

$= 1.39$ for emergency and faulted conditions

7.2.5.4 The maximum allowable flaw depth is limited to 75% of pipe wall thickness.

For axial flaws [A.37: H-5420]

$$\sigma_n = \frac{\sigma_f}{SF} \left[\frac{t/a - 1}{t/a - 1/M_2}\right]$$

Eqn. 14
where:

\[ M_2 = \left[ 1 + \frac{1.61I^2}{(4RT)} \right]^{1/2} \]  \hspace{1cm} \text{Eqn. 15}

\[ \sigma_f = 2.4S_m \]
\[ \sigma_n = \text{nominal hoop stress} = \frac{PD}{2t} \]
\[ D = \text{nominal outside diameter of the pipe} \]
\[ l = \text{total flaw length} \]
\[ a = \text{flaw depth} \]
\[ R = \text{mean radius of the pipe} \]
\[ t = \text{nominal thickness} \]
\[ SF = \text{Safety Factor; 3.0 for Level A and B Service Loadings, 1.5 for Level C and D Service Loadings} \]

7.2.5.5 Furthermore \( l < l_{\text{crit}} \) where \( l_{\text{crit}} \) is determined by the condition for the stability of through-wall flaws \( \sigma_n = \sigma_f / M_2 \).

7.2.5.6 Note flaw depths \( a \), and \( a_0 \), determined from eqn. 14 shall be used in the acceptance criteria of IWB 3652(a) [A.37] to determine the acceptability of the flawed pipe for continued service.

7.3 If \( 0.2 \leq SC < 1.8 \), elastic-plastic fracture mechanics (EPFM) techniques should be used in determining the allowable flaw size. Flow chart for materials meeting the EPFM criteria is provided in Section XI, Appendix H Article H-6000 and shown in Figure 10. Tables are provided in Appendix H for the determination of allowable flaw size. These tables are based on limit load analyses, but stress multipliers are provided to convert the EPFM analyses to equivalent limit load analyses using Z-factors provided in the Code.

7.3.1 Table H-5310-1 (Modified) - Circ. Flaws - Normal/Upset/Test Conditions

7.3.2 Table H-5310-2 (Modified) - Circ. Flaws - Emergency/Faulted Conditions

7.3.3 Table H-6410-1 - Axial Flaws - Normal/Upset/Test Conditions

7.3.4 Table H-6410-2 - Axial Flaws - Emergency/Faulted Conditions
7.3.5 Circumferential Flaws:

In using Tables H-5310-1 and H-5310-2 for circumferentially flawed welds, the primary membrane stress $P_m$, primary bending stress $P_b$, and expansion stress $P_e$ are considered in the load combination. The Stress Ratio (SR) for normal operating/upset/test conditions is calculated as:

$$SR = Z(P_m + P_b + P_e / 1.39) / S_m$$

7.3.6 The stress ratio for emergency/faulted condition is calculated as:

$$SR = Z(P_m + P_b + P_e / 1.39) / S_m$$

where $Z$ is the Z-factor provided in Tables H-6310-1 or Table 6310-2 of ASME Section XI, Appendix H.

7.3.7 In lieu of using these tables, an analytical solution based on modified limit load analysis may be used. The limit load equations provided in Section 7.2.5 are used. The allowable bending stress $S_b$ is determined as:

$$S_b = \frac{1}{SF} \left( \frac{P_b}{Z} - P_e \right) - P_m \left(1 - \frac{1}{Z(SF)}\right)$$

where:

- SF = safety factor
  - = 2.77 for normal operating/upset/test conditions
  - = 1.39 for emergency and faulted conditions.
- $P_b$ = Bending stresses at limit load for primary and expansion loads
- $Z$ = Load multiplier for ductile flaw extension

7.3.8 If more margin in the allowable flaw size is desired for ferritic pipe material exhibiting EPFM characteristics ($0.2 \leq SC < 1.8$), actual J-Integral/Tearing Modulus instability analysis can be performed. Models for performing such analyses are discussed in Attachment XV and provided in software programs which address these applications, see attachment XIV.

7.4 If $SC \geq 1.8$, linear elastic fracture mechanics (LEFM) techniques should be used in determining the allowable flaw size. A flow chart for materials meeting the LEFM criteria is provided in Section XI, Appendix H, Article 7000 and shown in Figure 11. This involves the evaluation of the applied stress intensity factor ($K_a$) and comparing it to allowable stress intensity factor ($K_c$).

7.4.1 For circumferential flaws, [A.37, H-7300, H-4221]

$$K_f = K_{fa} + K_{fb} + K_{fe} \leq K_c$$

Eqn. 19
where:

\[ K_{hc} = |J_{hc}|E'/1000|^5 \text{ ksi}/\text{in} \quad \text{Eqn. 3} \]

\[ J_{hc} = \text{Measure of material toughness due to crack extension at upper shelf, transition, and lower shelf temperatures. J integral at first flaw extension, in-lb/in}^2 \]

\[ E' = |E/(1-v^2)| \text{ ksi} \quad \text{Eqn. 4} \]

\[ K_{lm} = (SF) \cdot \left( \frac{\sigma}{\pi a} \right)^{0.5} F_m \text{ ksi/\text{in}} \quad \text{Eqn. 20} \]

where,

\[ \sigma = P_m = \frac{P}{2\pi R_l} \text{ ksi} \quad \text{Eqn. 21} \]

where

\[ P = \text{Total axial load on pipe including pressure, kips} \]

\[ K_{p} = \left( SF \cdot \frac{M}{(\pi R^2)} + P \cdot \frac{\pi a}{\sigma} \right)^{0.5} F_p \]

\[ = \left( SF \cdot \frac{M}{\sigma} + \frac{P}{\pi a} \right)^{0.5} F_p \quad \text{ksi/\text{in}} \quad \text{Eqn. 22} \]

\[ K_{tr} = \text{stress intensity factor due to residual stress with a safety factor of 1.0, ksi/\text{in}} \]

\[ K_{t} = \text{total applied stress intensity factor, ksi/\text{in}} \]

\[ F_{in} = 1.10 + x \left[ 0.15241 + 16.722 \left( \frac{x}{\pi} \right)^{0.855} - 14.944 \right] \quad \text{Eqn. 23} \]

\[ F_{in} = 1.10 + x \left[ -0.09967 + 5.0057 \left( \frac{x}{\pi} \right)^{0.565} - 2.8329 \right] \quad \text{Eqn. 24} \]

\[ x = a/t \]

\[ \frac{\theta}{\pi} = \text{ratio of crack length to pipe circumference} \]

\[ (SF) = \text{Safety Factor} \]

\[ = 2.77 \text{ for normal operating/upset} \]

\[ = 1.39 \text{ for emergency/faulted} \]

Note: K from transients are not considered per Code, [A.37].
\[ K_i = K_{in} + K_{ir} \leq K_f \]

where:

\[ K_{in} = (SF) \frac{pR}{t} \left( \frac{\pi \alpha}{Q} \right)^{0.5} F \text{ksi \sqrt{in}} \]

\[ K_{ir} = \text{stress intensity factor due to residual stress} \]
\[ K_{ic} = (J_{ic} E/1000)^{0.5} \text{ksi \sqrt{in}} \]

\[ \alpha = \frac{a/l}{(a/l)^2} \]

\[ Q = 1 + 4.593 \left( \frac{\alpha}{l} \right)^{1.05} \]

\[ F = 1.12 + 0.053\alpha + 0.0055\alpha^2 + (1.0 + 0.02\alpha + 0.0191\alpha^2) \left( 0 - R/t \right)^2 / 1400 \]

\[ pR = \text{Safety factor} \]
\[ (SF) = \begin{cases} 3.0 & \text{for normal operating (including upset and test) conditions} \\ 1.5 & \text{for emergency and faulted conditions} \end{cases} \]

\[ Q = 1 + 4.593 \left( \frac{\alpha}{l} \right)^{1.05} \]

\[ F = 1.12 + 0.053\alpha + 0.0055\alpha^2 + (1.0 + 0.02\alpha + 0.0191\alpha^2) \left( 0 - R/t \right)^2 / 1400 \]

\[ \alpha = \frac{a/l}{(a/l)^2} \]
Figure 1: Flaw Evaluation Procedure for Ferritic Piping
Figure 2: ASME Code Section XI Appendix H Flow Chart for Screening Criteria to Establish the Analysis Method [A.37]
### Through-Wall Residual Stress

<table>
<thead>
<tr>
<th>Wall Thickness</th>
<th>Axial</th>
<th>Circumferential</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 1 inch</td>
<td><img src="image1" alt="Axial Stress Diagram" /></td>
<td><img src="image2" alt="Circumferential Stress Diagram" /></td>
</tr>
<tr>
<td>≥ 1 inch</td>
<td>See Note 3</td>
<td><img src="image3" alt="0.5S Diagram" /></td>
</tr>
</tbody>
</table>

1. **S** = Yield stress
2. Considerable variation with weld heat input.
3. \( \sigma = \sigma_0 [1.0 - 6.91 (a/t)^2 + 8.69 (a/t)^3 - 0.48 (a/t)^4 + 2.03 (a/t)^4] \)

\( \sigma_0 \) = stress at inner surface \( (a = 0) \)

**Figure 3:** Recommended Axial and Circumferential Residual Stress Distributions for Circumferential Welds in Ferritic Pipe [A.13]
Figure 4: True Stress-Strain Curves for SA106 Gr. B and SA333 Gr. 6 at 550°F [A.13]
Attachment 7.9: Informational Attachment

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Figure 5: J-Resistance Behavior for A106 Gr. B (L-C Orientation) and A516 Gr. 70 (T-L Orientation) at 550°F [A.13]
Figure 6: $J/T$ Curves for Category 1 Materials [A.13]
Figure 7: J-R Curve for Category 2 Materials [A.13]
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Figure 8: J/T Curve for Category 2 Materials [A.13]
Figure 9: Flow Chart for Materials Meeting the Load Limit Criteria [A.37]
Figure 10: Flow Chart for Materials for which Ductile Flaw Extension May Occur Prior to Limit Load (EPFM) [A.37]
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Figure 11: Flow Chart for Materials Meeting the Linear Elastic Fracture Mechanics (LEFM) Criteria [A.37]
Figure 12: Stress Distribution in a Cracked Pipe -- Basis for Net Section Collapse Criteria for Austenitic Steel Pipe

Nominal stress in the uncracked section of pipe

\[ \sigma_1 - \text{Flow stress} \]

Limit Load (Net section plastic collapse)
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Attachment XIV: CLFE: Fracture Mechanics Software

1.0 Several personal computer-based software programs for performing fracture mechanics analysis of a wide variety of structural components and materials are available. The programs usually have many features and capabilities which are directly applicable to piping flaw and wall thinning evaluations addressed by this standard. These programs can be covered under vendor's nuclear quality assurance programs' safety related applications. Software programs can be used to perform fracture mechanics-based pipe flaw and wall-thinning evaluations described in this standard.

2.0 Typically the capabilities of these programs include:

2.1 Codes and Standards Evaluation

2.2 Linear Elastic Fracture Mechanics (LEFM)

2.3 Elastic Plastic Fracture Mechanics (EPFM)

3.0 Generally these software packages have major modules listed above which contain numerous sub-modules and options. These allow the user to input specific problem parameters, to perform the necessary analyses, to save all relevant data from the analyses for future use, and to obtain tabular and graphical output of results. They also contain detailed program description, including sample problems and a program verification manual in the program users manual.

4.0 Two of such software programs are mentioned in the list of references as B.6 and B.7
1.0 INTRODUCTION

1.1 The evaluation procedures provided in Attachments XII and XIII are based on ASME Code Section XI, Appendices C and H, respectively. It should be recognized that these appendices are non-mandatory, hence, alternate solutions can be obtained elsewhere in the literature. However, the acceptance criteria of IWB-3640 and IWB-3650 must be satisfied. The acceptance criteria can be satisfied by ensuring that the Code safety margins presented in Attachments XII and XIII are maintained at all times if alternate methods are used. In this attachment, alternate solutions are provided for linear elastic fracture mechanics (LEFM), elastic-plastic fracture mechanics (EPFM) and limit load analysis.

2.0 LINEAR ELASTIC FRACTURE MECHANICS

2.1 Linear elastic fracture mechanics (LEFM) is used for the determination of allowable flaw size for ferritic steels for which the screening criteria discussed in Attachment XIII is greater than or equal to 1.8. LEFM is also used to perform crack growth evaluations for both ferritic and austenitic stainless steel pipe.

2.2 LEFM assumes elastic behavior of the stresses in the pipe, including the region around the crack tip. The stress distribution near the crack tip depends on a single quantity termed "the stress intensity," generally designated as K. For loadings which produce an opening mode of displacement between the crack surfaces, the stress intensity factor is further designated as KI. Expressions have been developed in the literature for the calculation of the value of KI in terms of the applied load and the crack size for various combinations and shapes, and types of applied loading. All of these equations have an identical format:

\[ K_I = C \sigma \sqrt{a} \]  

where:

\[ \sigma = \text{nominal applied stress} \]
\[ a = \text{characteristic crack dimension such as crack depth for surface cracks} \]
\[ C = \text{non-dimensional constant whose value depends on crack geometry, the ratio of the crack size to the size of the structural member and type of loading (tension, bending, etc.)} \]
2.3 Formulations for $K_1$ for various surface, subsurface and throughwall geometries have been presented in several sources \([A.23 \text{ to } A.27]\). Some of these references have $K_1$ solutions for cases where the stress varies through the thickness of pipe. One of the most widely used solutions for $K_1$ are the formulations developed by Raju and Newman \([A.16 \text{ and } A.17]\). The formulations assume an elliptical surface flaw in a cylinder in tension and bending. The advantage of Raju-Newman solution is that $K$ can be determined at various locations on the crack front. There are also several software programs to solve for $K$ (see Attachment XIV). In fact, solutions for $K$ versus crack size found in References A.23 through A.27 can be imported directly to the calculation procedure in Reference A.37 to perform fracture mechanics evaluations such as crack growth.

2.4 The basic principle of LEFM is that unstable propagation of an existing flaw will occur when the value of $K$ attains a critical value designated as $K_{ic}$. The $K_{ic}$, generally called the fracture toughness of the material, is a temperature-dependent material property. The value of $K_{ic}$ recommended for use by ASME Section XI for ferritic materials in the LEFM regime is presented in Attachment XIII. Recommendations for $K_{ic}$ values for ferritic steels in the LEFM regime are provided in ASME Section XI, Appendix H, Article H-4000 \([A.37]\). Other values for $K_{ic}$ are provided in Reference A.27. In some cases, the value of $K_{ic}$ for a material is not readily available. However, in LEFM regime only, another parameter called $J_{lc}$ (the elastic-plastic fracture toughness) when available can be converted to $K_{ic}$ using the relationship

$$K_{ic} = \sqrt{\frac{E J_{lc}}{1 - \nu^2}} \text{ksi} \sqrt{\text{in}}$$

Eqn. 2

where, $J_{lc}$ is in in-lb/in$^2$ units

2.5 In summary, the implementation of alternate LEFM fracture mechanics concept for evaluation of flawed piping consists of two steps:

2.5.1 Determine $K_{ic}$ properties of the material from the Code or from other references such as Reference A.27.

2.5.2 Determine the anticipated flaw size in the pipe and calculate the value of $K_1$ from the References A.23 through A.27. Safety factors shall be applied to the stresses to maintain Code safety margins. Compare $K_1$ to $K_{ic}$ to ensure $K_1$ is less than $K_{ic}$.

3.0 ELASTIC-PLASTIC FRACTURE MECHANICS

3.1 Background

3.1.1 Elastic-plastic fracture mechanics principles are used for determination of allowable flaw sizes for austenitic stainless steel piping flux weldments and ferritic piping for which the screening criterion discussed in Attachment XIII is between 0.2 and 1.8. These materials are ductile such that there is significant plastic deformation around the crack tip while the rest of the structure exhibits elastic behavior.
3.1.2 In the presence of the crack, the stress and strain at the tip can be characterized by a parameter called $J$, where $J$ is a path independent integral which is a measure of the work done around the vicinity of the crack under the applied loading. For loadings which produce an opening mode of displacement between the crack surfaces, the $J$-integral is further designated as $J_o$.

3.1.3 For linear elastic cases,

\[ J = \frac{K^2}{E} (1 - v^2) \quad \text{Eqn. 3} \]

3.1.4 Similar to the LEFM case, there is a parameter designated as $J_c$ which measures the fracture toughness of the material. The values of $K_c$ can be converted to $J_c$ using the above expression. However, unlike the linear elastic case, unstable crack growth does not occur when the value of $J_c$ is reached. Figure 1 shows the crack growth behavior of a typical ductile material. Upon reaching $J_c$, there is a region of stable crack growth before unstable growth occurs.

3.2 Engineering Approach for Calculating $J$

3.2.1 In lieu of determining the value of $J$ using very sophisticated finite element analyses, several simple expressions have been enveloped for various cracked pipe configurations in References A.15, A.26, A.27 and A.42. The formulations in all these references assume that the material stress-strain behavior can be represented by the Ramberg-Osgood power law equation of the form:

\[ \frac{\varepsilon}{\varepsilon_o} = \frac{\sigma}{\sigma_o} + a \left( \frac{\sigma}{\sigma_o} \right)^n \quad \text{Eqn. 4} \]

where:

$\varepsilon$ and $\sigma$ = strain and stress, respectively

$\varepsilon_o$ and $\sigma_o$ = yield strain and yield stress, respectively

$a$ and $n$ = Ramberg-Osgood material coefficients

3.2.2 Values of $a$ and $n$ for typical piping materials used in the nuclear industry have been provided in Reference A.27.

3.2.3 For materials that can be represented by the Ramberg-Osgood stress-strain relationship, $J$ is generally represented as [A.42]:

\[ J = J_e + J_p \quad \text{Eqn. 5} \]

where:

$J_e$ = the elastic contribution

$J_p$ = the plastic contribution
3.2.4 The expressions for $J_a$ and $J_n$ have been provided in References A.15, A.26, A.27 and A.42 for various cracked pipe and loading configurations as listed below:

- $360^\circ$ part-wall crack in a cylinder under remote tension [A.27, A.42]

3.2.4.1 Through-wall flaws in a cylinder under remote tension, [A.15];

3.2.4.2 Through-wall flaws in a cylinder under remote bending, [A.15];

3.2.4.3 Through-wall flaws in a cylinder subjected to combined, tension and bending, [A.26];

3.2.4.4 Internally pressurized cylinder with an internal axial crack, [A.42].

3.2.5 Some of the J expressions have been incorporated into computer programs and are readily available for use. As a first step in the EPFM evaluation, the J calculated from the above references can be compared to $J_c$. It should be emphasized though that the Code safety factors should be applied to the piping loads to maintain Code margins. Values of $J_c$ for typical piping materials have been provided in Reference A.27.

3.3 Tearing Modulus Concept

3.3.1 Referring to Figure 1, it can be seen that even if the applied J from the piping loads is greater than $J_c$, there is a region of stable crack growth that can be sustained by the cracked piping before instability occurs. The three regions shown in Figure 1 can be summarized as follows:

3.3.2 For Equilibrium:

$$J_{\text{Applied}} = J_{\text{Material}} \Rightarrow \text{(No Crack Propagation)}$$

Eqn. 8

3.3.3 For Stability:

$$J_{\text{Applied}} > J_{\text{Material}} \Rightarrow \text{Crack Propagation}$$

Eqn. 9

$$\frac{dJ}{da}_{\text{Applied}} \leq \frac{dJ}{da}_{\text{Material}} \Rightarrow \text{Stability}$$

Eqn. 10

$$\frac{dJ}{da}_{\text{Applied}} > \frac{dJ}{da}_{\text{Material}} \Rightarrow \text{Instability}$$

Eqn. 11

3.3.4 For convenience, a parameter called the Tearing Modulus ($T$) is defined as (see figure 2):

$$T = \frac{dJ}{da} \frac{E}{\sigma_y^2}$$

Eqn. 12

3.3.5 Hence, if the relationship between $J$ and $a$ has been computed for the applied loading using the handbook solutions from References A.15, A.26, A.27 and A.42, the relationship between $J$ and $T$ for the applied loading can be determined.

3.3.6 The relationship between $J$ and the crack extension $\Delta a$ such as that shown in Figure 1 for a material is known as the J-R curve. The J-R curve is a material property that describes the resistance of a given material to continued ductile, stable crack extension under monotonic loading. From the J-R curve, a J-T curve can be constructed for the material using the above expression as shown in Figure 2. The J-T curve is applied to determine the instability point as shown in Figure 2. The J-R curve is generally represented as:
$J = C(\Delta a)^N$

Eqn. 13

where C and N are Power Law material coefficients dependent on the type of material. The typical values of C and N used for austenitic piping flux welds and ferritic piping are provided in Reference A.27. It should be cautioned again that in performing a J-T analysis in lieu of using the acceptance criteria of IWB-3640 or IWB-3650, the Code safety factors must be applied to the piping loads. J-T analyses can be performed using computer programs.

4.0 LIMIT LOAD ANALYSIS

4.1 Limit load analysis is used for the determination of allowable flaw size for base metal and non-flux weldments in austenitic stainless steel piping as well as ferritic piping for which the screening criterion, discussed in Attachment XIII, is less than 0.2. These materials are very tough, and therefore, there is no crack extension until the flawed pipe fails by collapse of the net section. The allowable flaw sizes for austenitic stainless steel piping in Attachment XII and ferritic piping in Attachment XIII are based on the procedures of ASME Section XI, Appendices C and H. In the development of the allowable flaw sizes in these appendices, it is assumed that the flaw geometry can be represented by a single flaw with constant depth (rectangular flaw) along the entire length. In the case where the actual shape of the flaw is not rectangular, the flaw shape conservatism in the Code procedures can be reduced. Some studies have shown that some relief in the allowable flaw size can be obtained if the flaw shape is assumed to be elliptical or parabolic [A.30]. An example of the comparison of allowable flaw size with various flaw shapes is shown in Figure 3. When multiple flaws are encountered during inspection, the conservative way to treat them is to assume a 360° flaw with the maximum depth associated with the flaws. However, it can also be shown that this conservatism can be reduced by treating these flaws as individual flaws [A.30]. The evaluation methodology presented in Reference A.30 is only applicable to flaws with symmetrical shapes.

4.2 For non-symmetric flaws and also for cases involving multiple flaws, development of the limit load equations becomes slightly complicated because a closed form solution is not possible. Hence, in these cases, an iterative process is used to determine the allowable plastic collapse bending moment on the cross section for a given axial load. For any arbitrary angle, the tension-to-compression axis can be determined and the two orthogonal moments can be calculated by integrating over the cross section. The resultant moment can be calculated as the square of the sum of these two moments. This process can be repeated at various discrete angles around the circumference of the pipe. The collapse moment is the minimum of all the resultant moments. This can be compared with the applied bending load to determine the safety margin which should be equal to or greater than the Code allowable for acceptance.

5.0 FINITE ELEMENT ANALYSIS

5.1 The methods presented in this section as well as in Attachment XII through XV can be used to solve almost all flawed pipe configurations that are encountered in nuclear power plant piping. Most of the solutions presented in this attachment were developed as a result of very sophisticated finite element analyses. In a very extreme case, finite element analysis can be used to add margins beyond the solutions presented in this attachment. In such analyses

5.2 special elements with very fine mesh refinements are required around the crack tip to determine $K_1$ or $J_1$. 
XVI: Figures

Figure 1: Overall Flow Chart For Evaluations
Localized Pipe Wall Thinning Evaluation (Attachments III - X)

\[ t_p < \text{or} \ (k)(t_p) \text{ for conditions as noted below} \]

Yes: Repair / Replace

No: Satisfy Licensing Code Equations using \( t_p \) in Global Pipe Section Properties (Att. VII)

Yes: Accept "As-IS"

No: Evaluation Using Localized Reduced Section Properties

- NP 5911-SP (Local Membrane, B31.G and Branch Reinforcement Methods): For Class 2, 3, B31.7 and B31.1 (Att. IX)
- GL 90-05 Methods (For Class 3 Mod. Energy Piping Only): Operable until NRC Approval (Attachment VIII)
- Code Case N-48B (For Class 2, 3, B31.1 and B31.7) Inoperable until NRC Approval (Attachment VII)
- Use of Alternate Methods: Attachment IX Section 3.0 for ASME Class 2, 3 and B31.1 Piping
- Finite Element Analysis with Licensing Code Safety Margins (Attachment X)

* Notes:
  - \( k = 0.3 \) for Class 1 and 2 Piping (ref. A.32 of Att. I) or
  - \( k = 0.2 \) for Class 3 High Energy Piping (ref. A.14 of Att. I) or
  - \( k_{t_n} = \) lesser of \( 0.3t_n \) and \( 0.5t_n \) for Class 3 Low Energy and B31.1 Piping (non-safety) (ref. A.28 of Att. I)

Figure 2: Flow Chart for Evaluation of Localized Pipe Wall Thinning
Figure 3: Flow Chart for Evaluation of Crack-like Flaws