Entergy

ENGINEERING STANDARD

EN-CS-S-008-MULTI Rev. 0 Effective Date: **1-1-2010**

Pipe Wall Thinning Structural Evaluation

Applicable Sites		Effective Date Exception	Applicable Sites		Effective Date Exception
IP-1	☒		ANO-1	☒	
IP-2	☒		ANO-2	☒	
IP-3	☒		GGNS	☒	
JAF	☒		RBS	☒	
PLP	☒		WF3	☒	
PNPS	☒		NP	☐	
VY	☒		HQN	☒	

Safety Related: X Yes
___ No

EC No(s).

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Approved by: R. Drake [signature] Date: 10/26/09
Engineering Standard Owner

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

Revision No.	Date	Changes
0		Original issue. This standard replaces: ENN-CS-S-008 & PS-S-001

TABLE OF CONTENTS

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

2.14 EN-DC-315, "Flow Accelerated Corrosion Program "

2.15 ENN-DC-185, "Through-Wall Leaks in ASME Section XI Class 3 Moderate Energy Piping Systems "

2.16 EPRI NSAC-202L-R3, "Recommandations for an Effective Flow Accelerated Corrosion Program", May 2006

2.17 EPRI CHECWORKS Steam/Feedwater Application Guidelines for Plant Modeling and Evaluation of Component Inspection Data, Report No. 1009599, Final Report, Sept. 2004

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, (in^2)

3.3 A_m - Predicted metal cross-section area with pipe wall thinning, (in^2)

3.4 A_o - Total cross-section area of pipe based on outside diameter, $\pi D_o^2/4$, (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_{Ups} - 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 $L_{m(a)}$ - 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 $L_{m(a),max}$ - 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 $L_{m(t)}$ - Maximum transverse extent of a local thinned area with wall thickness less than t_{min}, (in.),

(see Figure A-1 of Attachment 7.6)

3.18 $L_{m,avg}$ - Average of the extent of thickness less than t_{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, $(D_o - t_{nom})/2$, (in)

3.26 R_b - Pipe elbow bend radius, (in)

3.27 R_{min} – Mean radius of piping item based on the minimum wall thickness, (in)

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

3.29 R_o - Pipe outside radius, $D_o/2$, (in)

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

3.31 S_A - Pipe thermal expansion allowable stress, (psi)

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

3.33 S_{Nor} - Pipe axial stress at Normal Conditions or Stress Due to Sustained Loads [2.1], (psi)

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

3.35 S_{Fau} - Pipe axial stress at Faulted Conditions, (psi)

3.36 S_h - Pipe allowable stress at operating temperature, (psi), [see Appendix A of Ref. 2.1].

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

3.38 S'_{The} - Pipe thermal expansion stress for the thinned section, (psi)

3.39 S_p - Pipe axial stress due to pressure, (psi)

3.40 S_{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_{meas} - Minimum measured pipe wall thickness of the latest inspection, (in)

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

3.44 $t_{min,pipe}$ – Minimum required pipe wall thickness for straight pipe, (in)

3.45 t^a_{min} - Minimum required pipe wall thickness for axial stress, (in)

3.46 t'_{min} - Minimum required pipe wall thickness required for hoop stress, axial stress and larger than βt_{nom} ,(in)

3.47 t_{nom} - Pipe nominal wall thickness, (in)

3.48 t_P - Minimum predicted pipe wall thickness at the next inspection, (in)

3.49 Y - Service years between the latest and the next inspections, (years, or time unit)

3.50 Z_{min} - Predicted minimum section modulus for the thinned pipe section, including consideration
of the shift of the neutral axis of the thinned pipe section, (in^3)

3.51 W_r - Wear Rate, (in/year, or in/time unit)

3.52 Other

β A factor : 0.3 for Class 1 and 0.2 for Class 2 or 3 piping

δ The distance from the center of pipe to the center of gravity of the pipe metal thinned section, (in)

γ A factor of 1.143 (= 1 / 0.875)

θ Maximum angle (in degrees) from center of outer one-half of elbow to the location of thinned area being evaluated, as measured in the pipe cross section (see Figure 2)

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_r) shall be obtained from the FAC engineer, as applicable. Otherwise, it shall be determined as provided in Attachment 7.7.

Calculate t_P :

$t_P = t_{meas} - SF*W_r * Y$ [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;

Screening Criteria	Actions
$t_P \geq 0.875 * t_{nom}$ [2]	Accept as is
$0.875 * t_{nom} > t_P \geq 0.3 * t_{nom}$ for Class 1 $\geq 0.2 * t_{nom}$ for Class 2 & 3	Evaluate
$0.3 * t_{nom} > t_P$ for Class 1 $0.2 * t_{nom} > t_P$ for Class 2 & 3	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) (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_{min}:

$t_{min} = ((P * D_o) / [2*(S_h + 0.4*P)]) + A$ (3)

Hoop Stress Requirements	Actions
$t_P \geq t_{min}$	Accept for hoop stress
$t_P < t_{min}$	Replace or repair (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 CC N-513-2 can be used without NRC approval.

Note: (3) a. For reducers (see Figure 3), t_{min} shall be equal to t_{min} of straight pipe connected to
the reducer end. For the conical portion of the reducer, t_{min} shall be that of the larger diameter end.
b. For inner portion of elbows and pipe bends (see Figure 2), excluding a region within1.5*$(R_{nom}*t_{nom})^{0.5}$ of butt welds, t_{min} shall be equal to $[0.5+0.5/(1+(R_o/R_b)*\cos\theta)]*t_{min\text{-}pipe}$.
c. For branch connections and tees, except at regions providing reinforcement of the opening required by B31.1 Code, t_{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_{Nor}, S_{Ups}, S_{Emg}, S_{Fau}, & S_{The}) and their allowable stresses [$\gamma*K_{Nor}*S_h$, $\gamma*K_{Ups}*S_h$, $\gamma*K_{Emg}*S_h$, $\gamma*K_{Fau}*S_h$, & $\gamma*S_A$] 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^a_{min}, to calculate the ratio of old and new section modulus;

$Z/Z' = [D_o^4 - (D_o-2t_{nom})^4]/[D_o^4 - (D_o - 2t^a_{min})^4]$

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

Normal Conditions:

$\gamma * K_{Nor} * S_h - [P * D_o/4t^a_{min} + (i'/i) * (S_{Nor} - P * D_o/4t_{nom}) * (Z/Z')] \geq 0$ .... [Eq. 1]

Upset Conditions:

$\gamma * K_{Ups} * S_h - [P * D_o/4t^a_{min} + (i'/i) * (S_{Ups} - P * D_o/4t_{nom}) * (Z/Z')] \geq 0$ .... [Eq. 2]

Emergency Conditions:

$\gamma * K_{Emg} * S_h - [P * D_o/4t^a_{min} + (i'/i) * (S_{Emg} - P * D_o/4t_{nom}) * (Z/Z')] \geq 0$ .... [Eq. 3]

Faulted Conditions: (if required)

$\gamma * K_{Fau} * S_h - [P * D_o/4t^a_{min} + (i'/i) * (S_{Fau} - P * D_o/4t_{nom}) * (Z/Z')] \geq 0$ ....[Eq. 4]

Normal + Thermal Expansion:

$\gamma * (S_h + S_A) - [P * D_o/4t^a_{min} + (i'/i) * (S_{Nor} - P * D_o/4t_{nom} + S_{The}) * (Z/Z')] \geq 0$[Eq. 5]

The minimum of t^a_{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.

Axial Stress Requirements	Actions
$t_P \geq t^a_{min}$	Accept for axial stress
$t_P < t^a_{min}$	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 CC N-513-2 can be used.

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:

$S_p = P * A_i/A_m$

The axial bending stress, S_b, for various loading conditions shall be determined by:

$S_b = (M_b + P*A_o*\delta)/Z_{min}$

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

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

where $K = \gamma*K_{Nor}$, $\gamma*K_{Ups}$, $\gamma*K_{Emg}$, and $\gamma*K_{Fau}$ 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;

$S'_{The} = (i'/i)*(Z_{nom}/Z_{min}) * S_{The} \leq \gamma*S_A$

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_p 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:

Critical Buckling Stress = $8.46*E*(t_{ave}/b)^2$

(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 $(R_o t)^{0.5}$ from the weld centerline.

4. When the width of wall thinning W_m that exceeds t_{min}, is $\leq 0.5(R_o t)^{0.5}$ 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:

$RSL = (t_{meas} - t'_{min})/(SF^*W_r)$

Where t'_{min} = Maximum of (t_{min}, t^a_{min}, $\beta^* t_{nom}$)

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].

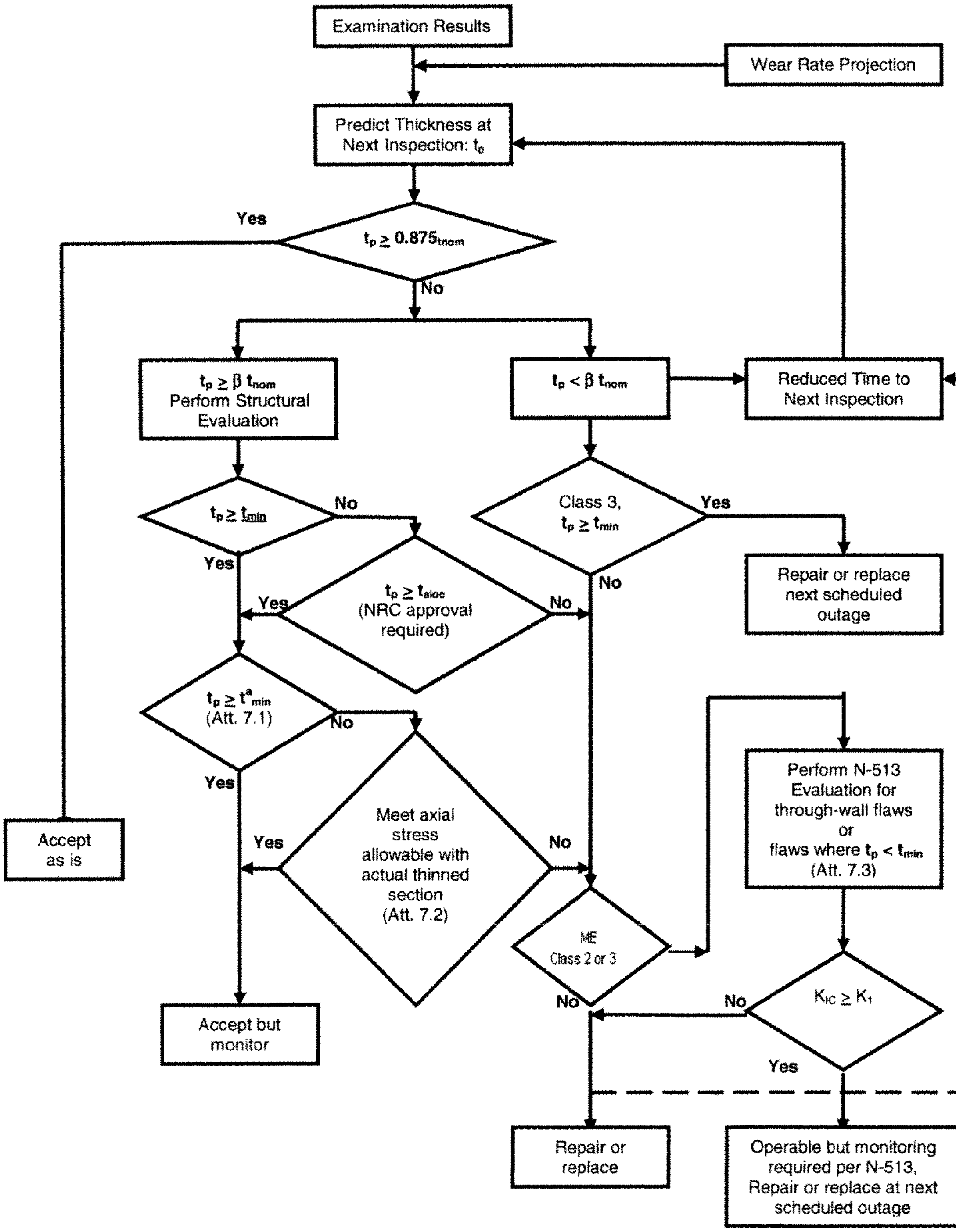


Figure 1: Logic Diagram for Pipe Wall Thinning Evaluation

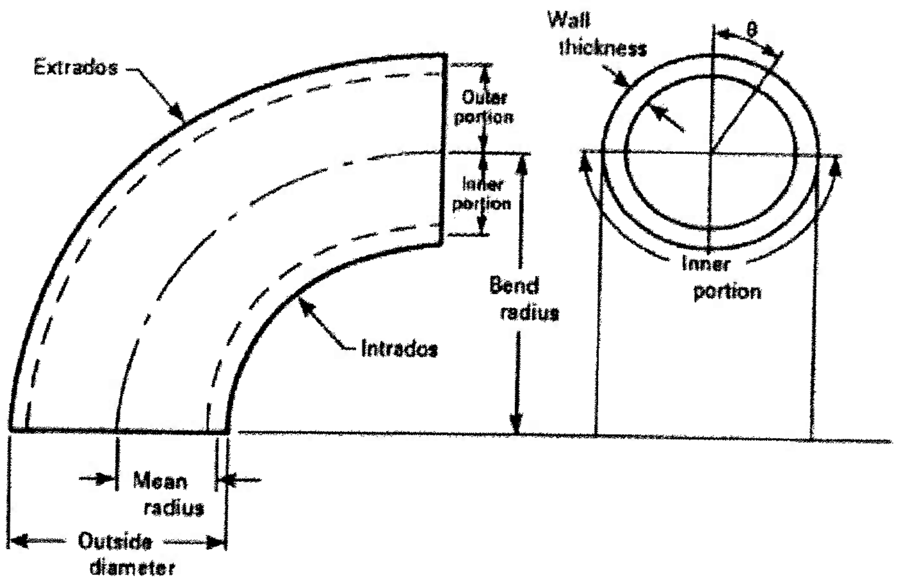
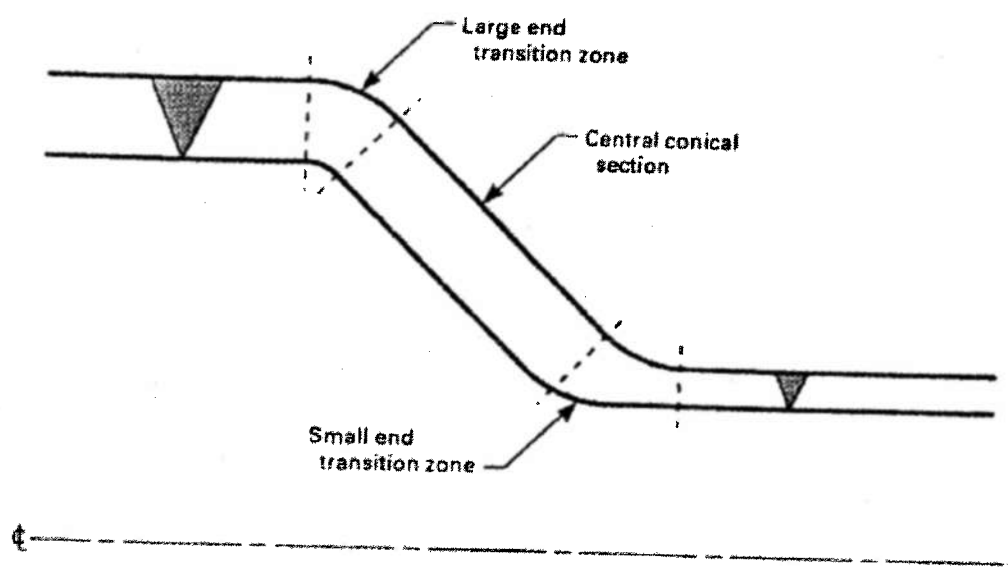
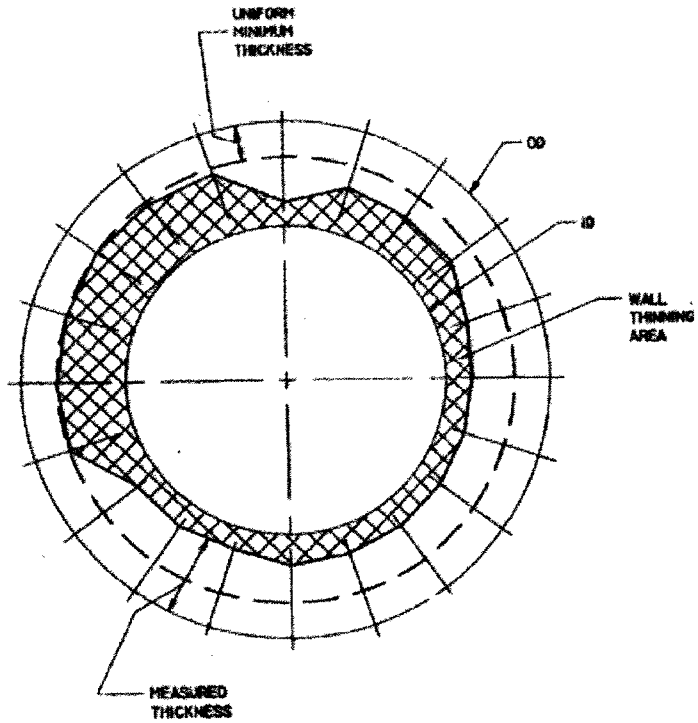


Figure 2: Elbow and Nomenclature



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 3: Zone of Reducer



1.1.1.1.1.1.1.1.1 Figure 4: A Typical Thinned Pipe Cross-Section

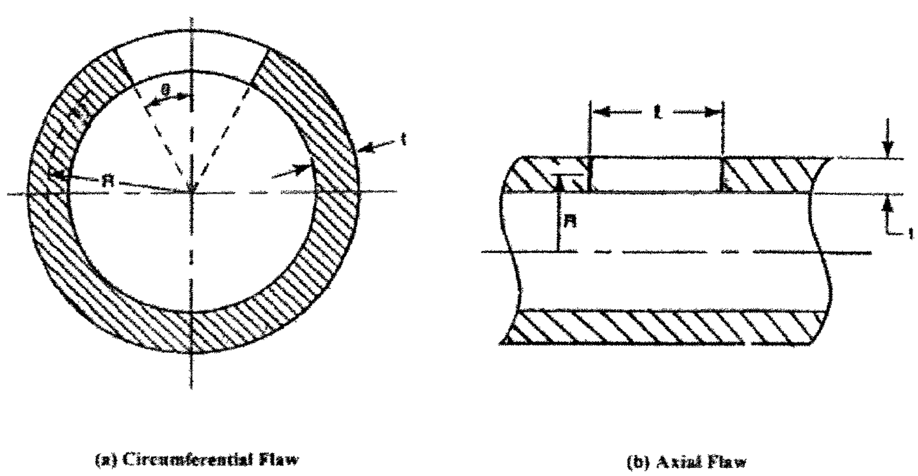


Figure 5: Through-Wall Flaw Geometry

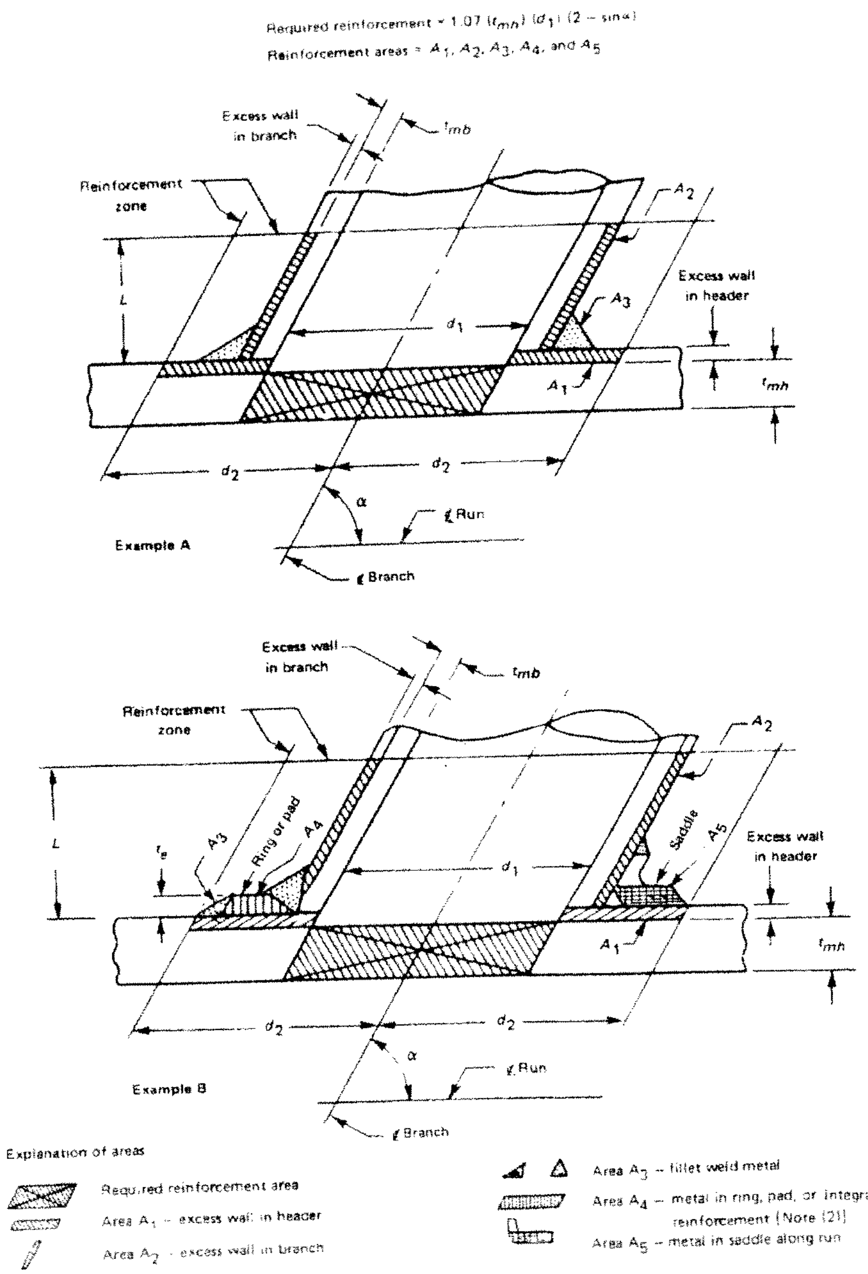


Figure 6: Reinforcement of Branch Connections
[Per ANSI B31.1, Figure 104.3.1 (d)]

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-001as Informational Attachment

7.9 Informational Attachment

Attachment 7.1 Example of Wall Thinning Evaluation Based on Uniformly Thinned Section
Sheet 1 of 2

1. Design Parameters (Boxed values are input)

D_o: Outside Diameter, (in)		3.5
t_{nom} : Nominal Thickness, (in)		0.216
Material		A106 GB, SML
P : Design Pressure, (psi)		325
T : Design Temperature, (°F)		280
S_h : Allowable Stress at Design Temperature, (psi)	(See App. A of B31.1)	15000
S_A : Thermal Expansion Allowable Stress , (psi)		22500
A : An additional thickness per Section 104.1 of B31.1, (in)		0

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

t_{meas} : Measured thickness of latest inspection, (in)		0.080
W_r : Wear Rate (in/yr)	(1)	0.00250
Y : Service years between the latest and next inspections, (yr)		2
SF : Safety factor		1.1
Projected thermal cycles between the latest and next inspections		70
$t_P = t_{meas}$ - SF*W_r*Y, (in)		0.0745
$R_o/t_p \le 50$, "OK"; or > 50, "Buckling Evaluation Required"	R_o/t_p = 23	OK

3. Screening Rules for Pipe Wall Thinning

Rule 1: Acceptance Standard = 0.875*t_{nom}	(2), (3)	0.189
Rule 2: Minimum Required Thickness		
0.3*t_{nom} for Class 1		0.065
0.2*t_{nom} for Class 2 or 3		0.043
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	Structural Evaluation Req'd
Class 2 or 3 piping	Structural Evaluation Req'd

4. Structural Evaluation

a. Minimum Thickness for Hoop Stress :

$t_{min} = P*D_o/[2(S_h+.4*P)] + A$, (in)	(4)	0.038

b. Minimum Thickness for Axial Stress :

Is the thermal expansion stress required to be evaluated?	Yes
(No for $t_p \ge 0.75*t_{nom}$ and cycles $\le$ 150; Yes for otherwise)	
K_{Nor} : Allowable stress increase factor for Normal Condition	1.0
K_{Ups} : Allowable stress increase factor for Upset Condition	1.2
K_{Emg} : Allowable stress increase factor for Emergency Condition	1.8
γ : Allowable stress increase factor for CC-N-597	1.143

Attachment 7.1 Example of Wall Thinning Evaluation Based on Uniformly Thinned Section

Sheet 2 of 2

Original Piping Stresses

S_{Nor} : Normal Condition Stress, (psi)		2500
S_{Ups} : Upset Condition Stress, (psi)		5600
S_{Emg} : Emergency Condition Stress, (psi)		7800
S_{The} : Thermal Expansion Stress, (psi)		8000
Let t^a_{min} =	(5)	**0.053**
i =		1
i' =	(6)	1
i' / i =		1
$Z/Z' = [D_o^4 - (D_o-2t_{nom})^4]/[D_o^4 - (D_o-2t^a_{min})^4]$		3.55

Allowable Stress - Axial Stress ≥ 0

Normal conditions:	$\gamma*K_{Nor}*S_h - [P*D_o/4t^a_{min} + (i'/i)*(S_{Nor} - P*D_o/4t_{nom})*(Z/Z')] \geq 0$	7568
Upset conditions:	$\gamma*K_{Ups}*S_h - [P*D_o/4t^a_{min} + (i'/i)*(S_{Ups} - P*D_o/4t_{nom})*(Z/Z')] \geq 0$	0
Emergency conditions:	$\gamma*K_{Emg}*S_h - [P*D_o/4t^a_{min} + (i'/i)*(S_{Emg} - P*D_o/4t_{nom})*(Z/Z')] \geq 0$	2483
Normal and Ther. Expansion conditions:	$\gamma*(S_h + S_A) - [P*D_o/4t^a_{min} + (i'/i)*(S_{Nor} - P*D_o/4t_{nom} + S_{The})*(Z/Z')] \geq 0$	4907

c. Minimum Required Thickness

Class 1:	$t'_{min} = Max. [t_{min}, t^a_{min}, 0.3*t_{nom}]$, (in);	Acceptable if $t_P \geq t'_{min}$	0.065	Yes
Class 2 & 3:	$t'_{min} = Max. [t_{min}, t^a_{min}, 0.2*t_{nom}]$, (in);	Acceptable if $t_P \geq t'_{min}$	0.053	Yes

5. Remaining Service Life (RSL)

Class 1:	$RSL = [t_{meas} - t'_{min}]/(SF*W_r)$, (yr)	5.5
Class 2 & 3:	$RSL = [t_{meas} - t'_{min}]/(SF*W_r)$, (yr)	9.9

Notes:

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

(2) The acceptance standard ($0.875t_{nom}$) 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_{nom} 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_{nom} of the pipe size at the larger end.

(4) The formula is applicable for straight pipes, bends, and elbows.
For reducers, t_{min} at each end shall be equal to t_{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_{min} 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^a_{min} 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.)

D_o : Pipe OD, (in)	18
R_o : Pipe outside radius, = $D_o/2$, (in)	9
t_{nom} : Pipe nominal wall thickness, (in)	0.375
Y' : Total service years up to latest inspection, (yr)	24
Y : Service years between latest inspection and next inspection, (yr)	2
N : Total no. of thickness measurements (equal grid) in circumferential direction (1)	20
$\Delta\theta = 2\pi/N$, angle of each grid, (rad) (where π = 3.142)	0.314

n	$(t_{meas})_n$	$(t_p)_n$	R_{in}	θ_n	A_{in}	A_{mn}	B_{iyn}	B_{ixn}	I_{xn}	I_{yn}	I_{xyn}
		(in.)	(in.)	(rad)	(in^2)	(in^2)	(in^3)	(in^3)	(in^4)	(in^4)	(in^4)
1	0.221	0.207	8.79	0.00	12.1	0.58	71.2	0.0	45.8	0.0	0.0
2	0.226	0.212	8.79	0.31	12.1	0.59	67.6	22.0	42.5	4.5	13.8
3	0.222	0.208	8.79	0.63	12.1	0.58	57.6	41.8	30.1	15.9	21.9
4	0.280	0.271	8.73	0.94	12.0	0.76	40.9	56.3	20.5	38.9	28.2
5	0.295	0.288	8.71	1.26	11.9	0.80	21.4	65.9	6.0	56.8	18.5
6	0.297	0.290	8.71	1.57	11.9	0.81	0.0	69.2	0.0	63.2	0.0
7	0.294	0.287	8.71	1.88	11.9	0.80	-21.4	65.9	6.0	56.6	-18.4
8	0.292	0.284	8.72	2.20	11.9	0.79	-40.8	56.1	21.5	40.7	-29.5
9	0.292	0.284	8.72	2.51	11.9	0.79	-56.1	40.8	40.7	21.5	-29.5
10	0.283	0.275	8.73	2.83	12.0	0.76	-66.2	21.5	54.3	5.7	-17.7
11	0.314	0.308	8.69	3.14	11.9	0.86	-68.8	0.0	67.1	0.0	0.0
12	0.304	0.297	8.70	3.46	11.9	0.83	-65.6	-21.3	58.6	6.2	19.1
13	0.304	0.297	8.70	3.77	11.9	0.83	-55.8	-40.6	42.4	22.4	30.8
14	0.138	0.116	8.88	4.08	12.4	0.33	-43.2	-59.4	9.0	17.1	12.4
15	0.137	0.115	8.88	4.40	12.4	0.32	-22.7	-69.9	2.5	23.4	7.6
16	0.139	0.117	8.88	4.71	12.4	0.33	0.0	-73.4	0.0	26.4	0.0
17	0.140	0.118	8.88	5.03	12.4	0.33	22.7	-69.8	2.5	24.1	-7.8
18	0.151	0.130	8.87	5.34	12.4	0.37	42.9	-59.1	10.1	19.1	-13.9
19	0.161	0.141	8.86	5.65	12.3	0.40	58.9	-42.8	20.7	10.9	-15.0
20	0.309	0.303	8.70	5.97	11.9	0.84	65.5	-21.3	59.7	6.3	-19.4
Min.	0.137	0.115		Σ_n =	A_i	A_m	B_{iy}	B_{ix}	I_x	I_y	I_{xy}
Ave.	0.240	0.228		Total	241.8	12.7	8.2	-18.1	539.9	459.6	1.0

Where n : Identification of measurement grid around circumference

$(t_{meas})_n$: Min. thickness measured in nth grid

$(t_p)_n$: Min. predicted thickness of nth grid at next inspection, = $(t_{meas})_n$ − SF*Y*W_r, where $W_r = (t_{nom} - (t_{meas})_n)/Y'$

R_{in} : Inside thinned radius = $R_o - (t_{meas})_n$ of nth grid

θ_n : Circumferential angle clockwise of nth grid (from vertical axis of pipe section)

$A_{mn} = (R_o^2 - R_{in}^2)*(\Delta\theta)/2$, $A_{in} = R_{in}^2*(\Delta\theta)/2$

$B_{iyn} = R_{in}^3*\cos(\theta_n)*(\Delta\theta)/3$, $B_{ixn} = R_{in}^3*\sin(\theta_n)*(\Delta\theta)/3$,

$I_{xn} = (R_o^4 - R_{in}^4)*\cos^2(\theta_n)*(\Delta\theta)/4$, $I_{yn} = (R_o^4 - R_{in}^4)*\sin^2(\theta_n)*(\Delta\theta)/4$, $I_{xyn} = (R_o^4 - R_{in}^4)*\sin(\theta_n)*\cos(\theta_n)*(\Delta\theta)/4$.

$A_m = \Sigma^N_{n=1} A_{mn}$, similar for A_i, B_{iy}, B_{ix}, I_x, I_y, and I_{xy} (The origin of x-y coordinates is at the center of pipe section.)

Attachment 7.2 Example of Axial Stress Calculation With Actual Thinned Section

SHEET 2 OF 2

Gravity center of pressure area ; $Y_p = B_{iy}/A_i$; $X_p = B_{ix}/A_i$; (in)	0.034	-0.075	
Gravity center of metal area : $X_m = -A_i/A_m{*}X_p$; $Y_m = -A_i/A_m{*}Y_p$; (in)	1.425	-0.649	
Moment inertias at C.G. of metal area : $I_{x'} = I_x - A_m{*}Y_m^2$, $I_{y'} = I_y - A_m{*}X_m^2$, & $I_{xy} = Ixy - A_m{*}X_m{*}Y_m$;(in^3)	534.6	433.8	12.74
Actual thinned Section: $I_{min} = \{I_x + I_y - [(I_x - I_y)^2 + 4{*}I_{xy}^2]^{0.5}\}/2$, $R_{max} = R_o + (X_m^2+Y_m^2)^{0.5}$, $Z_{min} = I_{min}/R_{max}$	432.2	10.57	40.9
Nominal section: I_{nom}, R_o, Z_{nom} (for t_{nom}= **0.375** in.); (in^3, in, in^2)	806.6	9.00	89.6
Uniformly thinned section: I, R_o, Z (for $(t_p)_{min}$ = **0.115** in.); (in^3, in, in^2)	258.8	9.00	28.8

2. Axial Stress for Actual Thinned Section

P : Design pressure, (psi)	150
$S_p = P{*}A_i/A_m/1000$, Axial stress for pressure based on the actual thinned section, (ksi)	2.86
$\delta = (X_m^2+Y_m^2)^{0.5}$, Eccentricity of thinned section, (in)	1.57
$M_p = (\pi{*}R_o^2){*}P{*}\delta/1000$, Bending moment due to eccentricity of pressure force, (k-in)	59.8

Operating Condition	Normal	Upset	Emerg.
S : Pipe axial stress based on nominal thickness [From Piping Stress Report], (ksi)	6.0	7.0	10.0
0.75i : [i : Stress Intensification for nominal thickness]	1.0	1.0	1.0
$M_b = (S - P{*}D_o/4t_{nom}/1000){*}Z_{nom}/(0.75i)$: Bending moment due code loadings, (k-in)	376	466	735
$M' = M_b + M_p$: Total bending moment for thinned section, (k-in)	436	526	795
0.75i' : [i' : Stress Intensification for average thinned thickness]	1.0	1.0	1.0
$S' = S_p + (0.75i'){*}M'/Z_{min}$: Actual stress based on the actual thinned section, (ksi)	13.5	15.7	22.3
γS_{allow} : Allowable stress, (ksi) (2)	17.1	20.6	30.9
Acceptable if $\gamma S_{allow} \geq S'$	Yes	Yes	Yes

Cyclic Operation	
S_{The} : Thermal stress range (ksi)	10
$S'_{The} = (i'/i){*}S_{The}{*}(Z_{nom}/Z_{min})$; (ksi)	21.9
γS_A : Thermal allowable stress; (ksi)	25.7
Acceptable if $\gamma S_A \geq S'_{The}$	Yes

Notes:

(1) It is recommended at least 18 measured wall thickness points around the circumference.

(2) γ =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)		20
t = Pipe wall thickness at flaw location (in)		0.150
t_{ave} = average wall thickness of pipe circumference based on UT report (in)	at section	0.250
t_{nom} = nominal pipe wall thickness (in)		0.375
p_d = Design Pressure (psi)		150
p_o = Operational Pressure (psi)	(< 275 psig)	90
T = Metal Temperature at evaluation(°F)	(< 200°F)	70
E = elastic modulus at T (ksi)		27800
ν = poison ratio		0.3
J_{1c} = material toughness (lb/in)		45
S = allowable stress for pipe (ksi)		15
i = SIF = stress intensification factor used in the stress analysis		1.00

Service Level		A	B	C	D
$p_dD_o/(4t_{nom})$ or from stress summary: Axial stress due to design pressure (ksi)		2.00	2.00	2.00	2.00
$s = p_dD_o/(4t_{nom}) + (0.75i)\sigma_b$: Piping Axial Stress (ksi, from stress output)		2.15	2.78	3.18	3.18
SF_m : Level A = 2.7; Level B = 2.4; Level c = 1.8; Level D = 1.3	[C-2621& 2622]	2.7	2.4	1.8	1.3
SF_b : Level A = 2.3; Level B = 2.0; Level c = 1.6; Level D = 1.4	[C-2621]	2.3	2.0	1.6	1.4
R_m = pipe mean radius (in) = $(D_o - t)/2$					9.925
$E' = E/(1 - \nu^2)$					30549
K_{1c} = material critical stress intensity factor $= (J_{1c} \cdot E'/1000)^{0.5}$ (ksi(in)$^{0.5}$)					37.08

B. Evaluate as a planar flaw in axial direction

(Based on LEFM C-7400 & N513-2, I-3.0)

Service Level		A	B	C	D
$c = \ell/2$ = Half axial flaw length (in)	, try "c" to make $K_{Ic} - K_I >= 0.0$	0.93	0.57	0.82	1.17
p = pressure for the service level condition		90	150	150	150
$\sigma_h = p' \cdot D_o/(2t)/1000$ (ksi)		6.00	10.00	10.00	10.00
For through wall flaw, a = c :					
$\lambda = c/(tR_m)^{0.5}$		0.76	0.47	0.68	0.96
$F = 1 + A\lambda + B\lambda^2 + C\lambda^3 + D\lambda^4 + E\lambda^5$		1.34	1.15	1.28	1.49
Where A= 0.0724 B= 0.6486 C= -0.2327 D= 0.0382		E=	-0.0023		
$K_{Ic} - K_I = K_{Ic} - K_{Im} = (SF_m)F\sigma_h(\pi c)^{0.5}$	(ksi(in)$^{0.5}$)	0.00	0.00	0.00	0.00
flaw length "2c"		1.86	1.14	1.65	2.33

Allowable Axial Flaw Length = Smaller "2c" of four service levels (in.) = 1.14

ATTACHMENT 7.3A EXAMPLE OF ASME CODE CASE N-513 EVALUATION FOR A THROUGH-WALL FLAW FOR CARBON STEEL

Sheet 2 of 2

C. Evaluate as a planar flaw in circumferential direction

						A	B	C	D
Service Level						A	B	C	D
$(0.75i) >= 1.0$						1.00	1.00	1.00	1.00
$\sigma'_b = (s - p_dD_o/(4t_{nom}))/(0.75i)$ (ksi)						0.15	0.78	1.18	1.18
$\sigma_b = \sigma'_b[D_o^4 - (D_o - 2t_{nom})^4]/[D_o^4 - (D_o - 2t_{ave})^4]$ (ksi)						0.221	1.148	1.737	1.737
p = pressure at the service level						90	150	150	150
$\sigma_m = pD_o/(4t_{ave})$: Axial stress due to service pressure (ksi)						1.80	3.00	3.00	3.00
K_{Ic} =						37.1	37.1	37.1	37.1
For through wall flaw, based on a = c									
c : Half circumferential flaw length, try "c" to make $K_{Ic} - K_I > 0.0$						1.41	0.94	1.06	1.27
$\alpha = c/(\pi R_m)$						0.045	0.030	0.034	0.041
$r = R_m/t$						66.2	66.2	66.2	66.2
	i=	0	1	2	3				
$A_m = A_{m0} + A_{m1}*r + A_{m2}*r^2 + A_{m3}*r^3$	A_{mi}	-2.0292	1.6776	-0.0799	0.0018	269.1	269.1	269.1	269.1
$B_m = B_{m0} + B_{m1}*r + B_{m2}*r^2 + B_{m3}*r^3$	B_{mi}	7.0999	-4.4239	0.2104	-0.0046	-706	-706	-706	-706
$C_m = C_{m0} + C_{m1}*r + C_{m2}*r^2 + C_{m3}*r^3$	C_{mi}	7.7966	5.1668	-0.2458	0.0054	840.8	840.8	840.8	840.8
$A_b = A_{b0} + A_{b1}*r + A_{b2}*r^2 + A_{b3}*r^3$	A_{bi}	-3.2654	1.5278	-0.0727	0.0016	243.4	243.4	243.4	243.4
$B_b = B_{b0} + B_{b1}*r + B_{b2}*r^2 + B_{b3}*r^3$	B_{bi}	11.363	-3.9141	0.1862	-0.0041	-620	-620	-620	-620
$C_b = C_{b0} + C_{b1}*r + C_{b2}*r^2 + C_{b3}*r^3$	C_{bi}	-3.1861	3.8476	-0.1830	0.0040	617.5	617.5	617.5	617.5
$F_m = 1 + A_m*\alpha^{1.5} + B_m*\alpha^{2.5} + C_m*\alpha^{3.5}$						3.30	2.30	2.54	3.00
$F_b = 1 + A_b*\alpha^{1.5} + B_b*\alpha^{2.5} + C_b*\alpha^{3.5}$						3.09	2.18	2.39	2.81
$K_{Ic} - K_I = K_{Ic} - [(SF_m)(\pi c)^{0.5}(\sigma_m F_m) + SF_b(\pi c)^{0.5}(\sigma_b * F_b)] \geq 0.0$						0.0	0.0	0.0	0.0
Flaw length (2c) =						2.82	1.88	2.11	2.55
Allowable Circumferential Crack Length = Smaller "2c" of 4 service levels (in.) =							**1.88**		

D. Check the hole penetration flow area

$t_{min} = p_dD_o/[2(S + 0.4p_d)]$ (inch)	0.100
L_{axial} = length of through wall crack for the hole penetration in the axial direction of the pipe (inch)	0.6
L_{circ} = length of through wall crack for the hole penetration in the circumferential direction of the pipe (inch)	1.2
A_1 = flow area of pipe (in^2)	291
A_2 = flow area per CC N-513-2 (in^2)	20
A_a = allowable flow area = smaller of A_1 and A_2	20
A_f = flow area of hole = $L_{axial}L_{circ}$	0.72
$A_f <= A_a$	**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

Parameter		A	B	C	D
D_o = Pipe OD (in)					20
t = Pipe wall thickness at flaw location (in)					0.150
t_{ave} = average wall thickness of pipe circumferential based on UT report(in)	at section				0.250
t_{nom} = nominal pipe wall thickness (in)					0.375
p_d = Design Pressure (psi)					150
p_o = Operational Pressure (psi)	(< 275 psig)				90
T = Metal Temperature at evaluation(°F)	(< 200°F)				70
E = elastic modulus at T (ksi)					27800
v = poison ratio					0.3
J_{1c} = material toughness (lb/in)					45
S_y = Material yield stress at T (ksi)					35
S_u = Material ultimate tensile strength at T (ksi)					60
i = SIF = stress intensification factor					1.00
Service Level		A	B	C	D
p_d*D_o/(4t_{nom}) or from UE&C stress summary; Axial stress due to design pressure (ksi)		2.00	2.00	2.00	2.00
s = $p_dD_o/(4t_{nom})$ + (0.75i)σ_b: Piping Axial Stress (ksi, from stress output)		3.88	7.06	7.82	7.82
SF_m : Level A = 2.7; Level B = 2.4; Level c = 1.8; Level D = 1. [C-2621 & 2622]		2.7	2.4	1.8	1.3
SF_b : Level A = 2.3; Level B = 2.0; Level c = 1.6; Level D = 1. [C-2621]		2.3	2.0	1.6	1.4
a/t = depth of flaw to wall thickness ratio (for through wall flaw, a/t = 1.0)					1.00
R_m = pipe mean radius (in) = (D_o - t)/2					9.925
E' = E/(1 - v^2)					30549
K_{1c} = material critical stress intensity factor =J_{1c}*E'/1000)$^{0.5}$ (ksi(in)$^{0.5}$)					37.08

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

Parameter		A	B	C	D
Service Level		A	B	C	D
p = pressure at service level		90	150	150	150
σ_h = $pD_o/(2t)$	(psi)	6000	10000	10000	10000
σ_f = $(S_y + S_u)/2$	(psi)	47500	47500	47500	47500
l_{all} = allow through wall axial flaw (inch) = $1.58(R_m t)^{0.5}([\sigma_f/(SF_m)\sigma_h]^2 - 1)^{0.5}$		5.3	3.3	4.7	6.8
Allowable Axial Flaw Length = l_{all} of four service levels (in.) =			**3.3**		

Attachment 7.3B Example of ASME Code Case N-513 Evaluation for a Through-Wall Flaw for Austenitic Steel

Sh. 2 of 2

C. Evaluate as a planar flaw in circumferential direction **(Based on Limit Load C-5320)**

	A	B	C	D
Service Level	A	B	C	D
$(0.75i) >= 1.0$	1.00	1.00	1.00	1.00
$\sigma_b' = [s - p_dD_o/(4t_{nom})]/(0.75i)$	1.88	5.06	5.82	5.82
$\sigma_b = \sigma_b'[D_o^4 - (D_o - 2t_{nom})^4]/[D_o^4 - (D_o - 2t_{ave})^4]$	2.763	7.442	8.564	8.564
p = pressure at the service level (psi)	90	150	150	150
$\sigma_m = p^*D_o/(4t_{ave})$: Axial stress due to internal pressure (ksi)	1.80	3.00	3.00	3.00
c = half crack length, trial & error until o.k. appears for both primary bending and membrane stress	15.8	11.7	12.5	13.5
$\theta = c/R_m$ (radian)	1.592	1.179	1.259	1.360
$\sigma_f = (S_y + S_u)/2$ (psi)	47500	47500	47500	47500
If $(\theta + \beta) <= \pi$, then flaws not penetrating the compressive side of pipe				
$\beta = 0.5[\pi - (a/t)\theta - \pi\sigma_m/43.4]$	0.71	0.87	0.83	0.78
$\sigma^c_b = (2\sigma_f/\pi)[2\sin\beta - (a/t)\sin\theta]$ (psi)	9175	18388	15945	13053
If $(\theta + \beta) > \pi$, then flaws penetrating the compressive side of pipe				
$\beta = \pi[1 - a/t - \sigma_m/\sigma_f]/(2 - a/t)$	-0.12	-0.20	-0.20	-0.20
$\sigma^c_b = (2\sigma_f/\pi)[2 - (a/t)]\sin\beta$ (psi)	16760	27817	27817	27817
Use σ^c_b	9175	18388	15945	13053
Check primary bending stress				
Allowable bending stress = S_c = $\sigma^c_b/SF_b - \sigma_m[1 - 1/$ (psi)	2856	7444	8633	8631
$S_c - \sigma_b >= 0$	93	2	68	67
	o.k.	**o.k.**	**o.k.**	**o.k.**
Check primary membrane stress				
$\varphi = \arcsin[0.5(a/t)\sin\theta]$	0.52	0.48	0.50	0.51
$\sigma^c_m = \sigma_f[1 - (a/t)(\theta/\pi) - 2\varphi/\pi]$ (psi)	7601	15151	13457	11485
Allowable membrane stress = $S_t = \sigma^c_m/SF_m$	2815	6313	7476	8835
$S_t - \sigma_m >= 0$	1015	3313	4476	5835
	o.k.	**o.k.**	**o.k.**	**o.k.**
Flaw length (2*c) =	31.6	23.4	25.0	27.0
Allowable circumferential Flaw Length = Smaller "2c" of four service levels (in.) =		**23.4**		

F. Check the hole penetration flow area

$t_{min} = p_dD_o/[2(S + 0.4p_d)]$ (inch)	0.100
L_{axial} = length of through wall flaw for the hole penetration in the axial direction of the pipe (Inch)	0.6
L_{circ} = length of through wall flaw for the hole penetration in the circumferential direction of the pipe (inch)	1.2
A_1 = flow area of pipe (in^2)	291
A_2 = flow area per CC N-513-2 (in^2)	20
A_a = allowable flow area = smaller of A_1 and A_2	20
A_f = flow area of hole = $L_{axial}L_{circ}$	0.72
$A_f <= A_a$	**Yes**

Attachment 7.4 Example of Minimum Wall Evaluation at Reinforcement Area of Tee

Sheet 1 of 1

1. Branch Connection Dimensions

(See Figure 6 for nomenclature and dimensions)

(Boxed values are input.)

α : Angle between axes of run and branch, (Deg.)	90
d_i : ID of branch, (in)	25.25
d_o : OD of branch, (in)	26
t_p : Min. predicted branch wall thickness, (in)	0.244
t_{min} : Min. required branch wall thickness, (in)	0.075
D_o : OD of run, (in)	36
T_p : Min. predicted run wall thickness, (in)	0.244
T_{min} : Min. required run wall thickness, (in)	0.092

2. Reinforcement Area Dimensions

d_1 : $d_i/\sin(\alpha)$, (in)	25.25
d_2 : "Half width" of reinforcing zone = Max(d_1, $t_p+T_p+d_1/2$) but not more d_i, (in)	25.25
L : Altitude of reinforcement zone outside of run = 2.5^*t_p, (in)	0.61
t_e : Thickness of reinforcement ring, pad or saddle, (in)	0.0
D_r = OD of reinforcement ring, pad or saddle (Effective only up to 2^*d_2); (in)	0.0

3. Reinforcement Area Required for Pressure

$A_{req} = 1.07^*T_{min}{}^*d_i{}^*[2-\sin(\alpha)]$, ($in^2$)	2.486

4. Reinforcement Area Provided

A_1 : Excess wall thickness in run = $d_2{}^*(T_p - T_{min})$, (in^2)	3.838
A_2 : Excess wall thickness in branch = $2L^*(t_p - t_{min})$, (in^2)	0.206
A_3 : Area provided by deposited weld metal beyond OD of run and branch, (in^2)	0.063
A_4 : Area provided by a reinforcing ring or pad = $(D_r - d_1)^*t_e$, (in^2)	0
A_5 : Area provided by a reinforcing saddle = $(D_r - d_o)^*t_e$, (in^2)	0
Total Area Provided : $A_{prov} = A_1 + A_2 + A_3 + (A_4 \text{ or } A_5)$; (in^2)	4.11

5. Acceptability of Thinning at Reinforcement Area

Acceptable if $A_{prov} \geq A_{req}$	Yes

Attachment 7.5 Plant Specific Allowable Stress Factors
Sheet 1 of 1

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)

Site	Normal K_{Nor}	Upset K_{Ups}	Emergency K_{Emg}	Faulted K_{Fau}
IP2	1.0	1.2	1.8	1.8 (2)
IP3	1.0	1.2	1.8	1.8 (3)
JAF	1.0	1.2	1.8	2.4 (4)
PNPS	1.0	1.2	1.8	2.4
VY	1.0	1.2	1.8	2.4 (4)

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_{aloc} : [2.4]

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

Case	Conditions	Applicable Limits	t_{aloc}/t_{min}
1	Limited Transverse Extent	$(R_{min}*t_{min})^{0.5} \geq L_{m(t)}$ (1)	From Column 3622.2 of Table A-1
2	Limited Axial & Transverse Extent	$2.65*(R_{min}*t_{min})^{0.5} \geq L_m$ and $t_{nom} > 1.13*t_{min}$	Larger value of $1 - 1.5*(R_{min}*t_{min})^{0.5}*(t_{nom}/t_{min}-1)/L$ and $0.353*L_m/(R_{min}*t_{min})^{0.5}$
3	Unlimited Transverse Extent	Case 1 or Case 2 not met	From Column 3622.4 of Table A-1

F. Local Wall Thickness Requirements

Hoop Stress Criteria	Actions
$t_P \geq t_{aloc}$	Accept for Hoop stress
$t_P < t_{aloc}$	Repair or replace

An example of local thinning evaluation for hoop stress is shown in this Attachment [Sht 6 & 7].

Notes: (1) For multiple thinned areas, the wall thickness is required to exceed t_{min} for a distance that is the greater of $2.5(R_{nom}t_{nom})^{0.5}$ or $2L_{m,avg}$ 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 $2.5(R_{nom}t_{nom})^{0.5}$ or $2L_{m(a),max}$ 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

Sheet 2 of 7

$\frac{L_{m(a)}}{\sqrt{R_{min} t_{min}}}$	Allowable Local Thickness t_{aloc}/t_{min}	
	-3622.2	-3622.4
0	0.100	0.100
0.20	0.100	0.261
0.23	0.100	0.300
0.26	0.100	0.375
0.32	0.100	0.477
0.38	0.100	0.551
0.45	0.100	0.616
0.50	0.100	0.651
0.60	0.100	0.703
0.70	0.182	0.742
0.83	0.300	0.778
0.85	0.315	0.782
0.90	0.349	0.794
1.00	0.410	0.813
1.20	0.505	0.841
1.40	0.572	0.860
1.60	0.622	0.873
1.80	0.659	0.883
2.00	0.687	0.891
2.25	0.714	0.897
2.50	0.734	0.900
2.75	0.750	0.900
3.00	0.763	0.900
3.50	0.787	0.900
4.00	0.811	0.900
4.50	0.834	0.900
5.00	0.858	0.900
5.50	0.882	0.900
6.00	0.900	0.900
>6.00	0.900	0.900

GENERAL NOTE:
Interpolation may be used for intermediate values.

Table A-1

Attachment 7.6 Recommendation for Safety Related Moderate Energy Class 2/3 and NON-SAFETY RELATED PIPING

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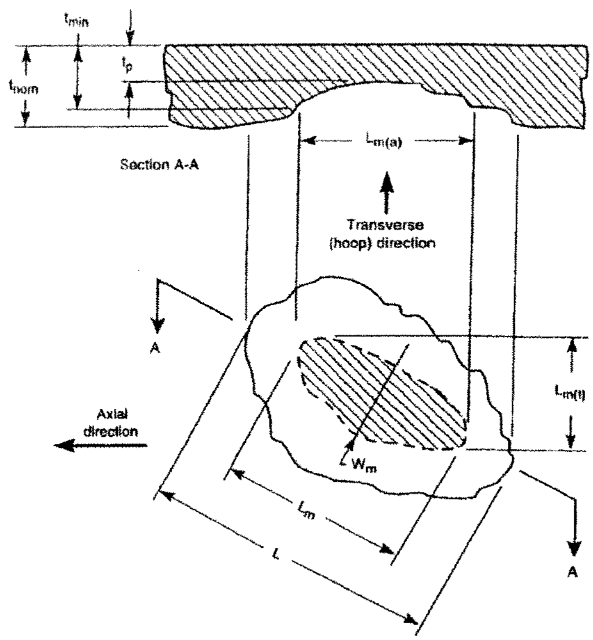

Figure A-1 Illustration of Nonplanar Flaw Due To Wall Thinning

Attachment 7.6 Recommendation for Safety Related Moderate Energy Class 2/3 and NON-SAFETY RELATED PIPING

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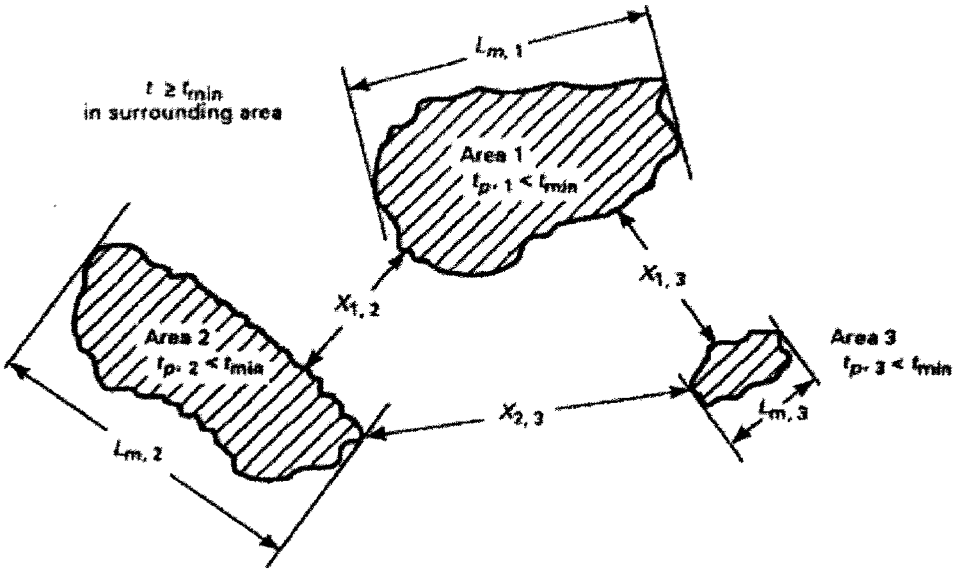


X_{ij} = minimum distance between areas i and j

$L_{m,i}$ = maximum extent of thinned area i

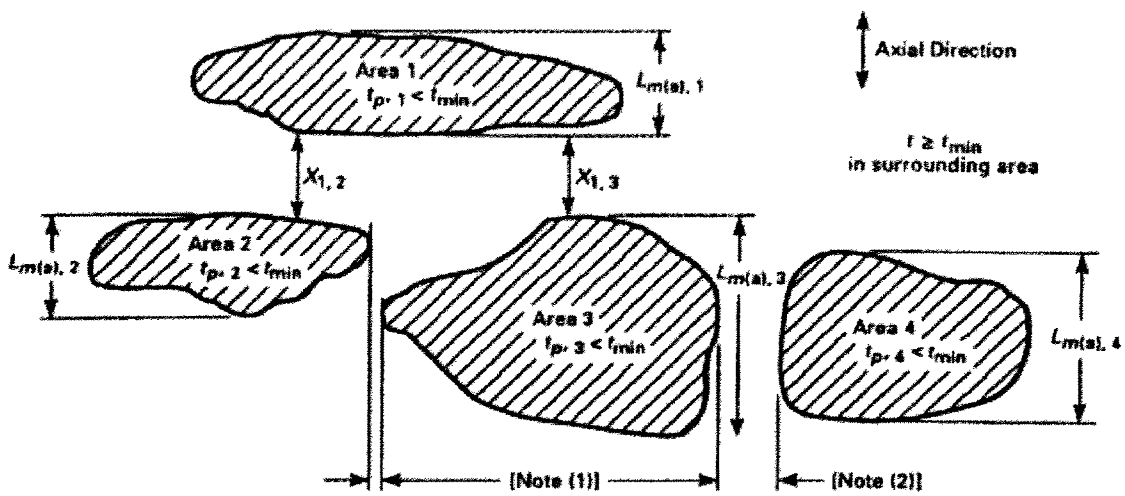
$L_{m,avg} = 0.5(L_{m,i} + L_{m,j})$

GENERAL NOTE:
Combination of adjacent areas into an equivalent single area shall be based on dimensions and extents prior to combination.

Figure A-2: Separation Requirements for Adjacent Thinned Areas

Attachment 7.6 Recommendation for Safety Related Moderate Energy Class 2/3 and NON-SAFETY RELATED PIPING

SHEET 5 OF 7



X_{ij} = minimum distance between areas i and j at any circumferential location on pipe

$L_{m(a),i}$ = maximum extent of thinned area i in axial direction

L_{max} = maximum of the extents $L_{m(a),i}$ and $L_{m(a),j}$ of two adjacent areas

NOTES:

(1) Areas need not be combined into single areas based on separation in the transverse direction, provided that transverse extents of individual adjacent thinned areas do not overlap.

(2) Combination of adjacent areas into an equivalent single area shall be based on dimensions and extents prior to any combination of adjacent areas.

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

Sheet 6 of 7

Attachment 7.6 : RECOMMENDATION FOR SAFETY RELATED MODERATE ENERGY CLASS 2/3 AND NON-SAFETY RELATED PIPING			
(NRC review and approval is required for Class 1 and High Energy Piping)			
1. Design Parameters			
(Boxed values are input.)			
D_o: Outside Diameter, (in)			16
t_{nom} : Pipe nominal thickness, (in)			0.5
p : design pressure [for N597-2] or maximum operating pressure at flaw location [for N-513]			275
S : allowable stress for pipe (psi)			15000
t_{min} : Minimum thickness required for hoop stress due to pressure, $= pD_o/[2(S + 0.4p)]$ (in)			0.146
t_P : Minimum predicted wall thickness at next inspection, (in)			0.330
σ_b : nominal pipe longitudinal bending stress resulting from all primary pipe loading (psi)			7000
R: R_{min} is used for CC N-597-2; R_o is used for CC N-513-2			
R_{min} : Pipe mean radius, $= (D_o - t_{min})/2$, (in)			7.93
R_o : Pipe radius, $= D_o/2$, (in)			8.00
2. Local Thinning Area Dimensions (See Figure 2 for illustration)			
The following dimensions shall be the dimensions predicted at the next inspection.			
L : Maximum length of area where thickness is less than t_{nom}, (in)			4
L_m : Maximum length of area where thickness is less than t_{min}, (in)			2
$L_{m(t)}$: Maximum length in transverse direction of area where thickness is less than t_{min}, (in)			1.5
$L_{m(a)}$: Maximum length in axial direction of area where thickness is less than t_{min}, (in)			1.2
$L_{m(a)} /(R_{min}{*}t_{min})^{0.5}$: Dimensionless length of local thinning in axial direction			1.12
Is CC-N513-2 applicable, input yes or no			no
Note: For CC N-513-2, apply to pipe & fitting at a distance <= $(R_o t)^{0.5}$ from weld center line			
3. Acceptance Thickness for Local Thinning, t_{aloc}			
		N-597-2	N-513-2
$(R{*}t_{min})^{0.5}$: Pipe characteristic length, (in)		1.07	1.08
Case 1: Local Thinning for Limited Trasverse Extent			
Applicable if $(R{*}t_{min})^{0.5} \geq L_{m(t)}$		**No**	**n/a**
$c_1 = (t_{aloc}/t_{min})$, see note 1		0.90	n/a
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 $2.65{*}(R{*}t_{min})^{0.5} \geq L_m$ and $t_{nom} > 1.13{*}t_{min}$		**Yes**	**n/a**
$c_{21} = (1.5{*}(R{*}t_{min})^{0.5}/L){*}(1 - t_{nom}/t_{min}) + 1.0$		0.019	n/a
$c_{22} = 0.353{*}L_m/ (R{*}t_{min})^{0.5}$		0.657	n/a
c_2 = Larger of (c_{21}, c_{22}) if applicable, or 1.0 if not		0.657	n/a
Case 3: Unlimited Transverse Extent			
$c_{31} = (t_{aloc}/t_{min})$, see note 2		0.830	n/a
$c_{32} = [0.5 + (t_{nom}/t_{min})(\sigma_b/S)]/1.8$			
c_3 = Larger of (c_{31}, c_{32})		0.830	n/a
Note 2: N513-2: from curve 2 of Fig. 3; N597-2: from table 3622-1, -3622.4			
t_{aloc} = Min (c_1, c_2, c_3) * t_{min}, (in)		0.096	
Acceptable if $t_P \geq t_{aloc}$		**Yes**	
b. Elbow and Bent Pipe			

Attachment 7.6 Recommendation for Safety Related Moderate Energy Class 2/3 and NON-SAFETY RELATED PIPING

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b. Elbow and Bent Pipe

R_b : Elbow radius, (in)	24
θ : Thinning location angle, See Fig. 2 for illustration (Deg.)	0
$t_{aloc} = (0.5+0.5/(1+(R_{min}/R_b{}^*\cos\theta)))\ ^*\ t_{min}$, (in)	0.128
Acceptable if $t_P \geq t_{aloc}$	yes

c. Reducer

d_0 : Maximum outside diameter of piping item at the thinned location, (in)	24
D_1 : Reducer larger end outside diameter ($=D_o$ assumed), (in)	24
α : Maximum cone angle at the center of a reducer, (degree)	45
$t_{aloc} = (d_0/D_1)/\cos\alpha\ ^*\ t_{min}$, (in)	0.103
Acceptable if $t_P \geq t_{aloc}$	yes

Notes applicable to Code Case N597-2:

(1) Local thinning evaluation shall not be allowed for the following :

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 thinned area predicted to be less than t_{min} exceeds D_i, where D_i is the nominal inside diameter of the branch connection.
2. At the small end transition of a reducer.
3. Inner portion of elbows, $t'_{min} = 0.5[1+1/(1+(R_b/R_o)^*\cos\theta)]^*t_{min,pipe}$, 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, $c_{21} = 1 - 0.935A_{rein}/(L_m{}^*t_{min})$; where A_{rein} = the reinforcement area available in the pipe wall based on t_p distribution in excess of t_{min} 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].

Attachment 7.7 Recommended Guidance and Methods for Calculation of Wear Rates
Sheet 1 of 3

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

For each band: t_{init} = larger of t_{nom} or t_{max}

$$Wear = t_{init} - t_{meas}$$

The component maximum wear is the largest of the individual band wear values. The component initial thickness is than 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_{init}) of each area is assumed to be the larger of the nominal thickness or the maximum thickness found in each area, (t_{max}).

For each area: t_{init} = larger of t_{nom} or t_{max}

$$Wear = t_{init} - t_{meas}$$

The component maximum wear is the largest of the individual area wear values. The component initial thickness is than 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.

Attachment 7.7 Recommended Guidance and Methods for Calculation of Wear Rates
Sheet 2 of 3

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 1

Component Type	Band Method	Area Method	Moving Blanket Method
Elbow	NO	NO	YES
Tee	YES (*)	NO	YES (*)
Straight Pipe	YES	NO	YES
Concentric Reducer/Expander	YES	NO	NO
Eccentric Reducer/Expander	NO	NO	YES
Nozzle	YES (*)	NO	NO

* 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:

Attachment 7.7 Recommended Guidance and Methods for Calculation of Wear Rates
Sht 3 of 3

The lowest recorded thickness value for all grid points is used as the measured thickness (t_{meas}).

t_{init} = larger of t_{nom} or t_{max}

Wear = t_{init} - t_{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

Cases	Moving Blanket	Point-to-Point
Baseline data and subsequent outages	NO	YES
No baseline data with 1 or 2 outages	YES	YES [1]
No baseline data with more than 2 outages	YES [2]	YES [2]

[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

Page 1 of 2

PS-S-001 Attachment	Title	Acceptability	Remark
I	References for pipe wall thinning (PWT) and crack-like flaw evaluation (CLFE).	Yes (see Attachment 7.9)	References are either built into section 2.0 or the spread sheets in the EN standard.
II	Terminology and Nomenclature for PWT and CLFE	Yes (see Attachment 7.9)	Nomenclature is either built into section 3.0 or the spread sheets in the EN standard.
III	Inputs / Requirements common for PWT and CLFE	Yes (see Attachment 7.9)	Inputs are built into the spread sheets in the EN standard.
IV	Inputs / Requirements for evaluation of PWT	Yes (see Attachment 7.9)	Inputs are built into the spread sheets in the EN standard.
V	Inputs / Requirements for CLFE	Yes (see Attachment 7.9)	Inputs are built into the spread sheets in the EN standard.
VI	Definition of PWT and CLFE	Yes (see Attachment 7.9)	
VII (removed)	PWT Evaluation: Code Evaluation Procedure	No CC N-480 was superseded	See Figure 1, Att. 7.1, 7.2, 7.6 in the EN standard.
VIII (removed)	PWT Evaluation: NRC Generic Letter 90-05 Methods	No, CC N-480, methodology required NRC approval	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 & 3 piping.
IX (removed)	PWT Evaluation: Alternate Methods	No CC N-480 was superseded	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 & 3 piping local thinning $t_{aloc} < t_p < t_{min}$ evaluation. Moderate energy class 2 & 3 piping does not need to have NRC approval.

Attachment 7.8: Guide for using PS-S-001 as informational attachment

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

Attachment 7.9: Informational Attachment
Page 1 of 93

Attachment I: References for Pipe Wall Thinning and Crack-Like Flaw Evaluation

REFERENCES

A. Additional References Used in This Standard and Attachments:

A.1 ASME Boiler and Pressure Vessel Code, Section III, Subsections NB, NC, and ND 1974 Edition through Summer 1975 Addenda.

A.2 ASME Boiler and Pressure Vessel Code, Section III, Subsections NB, NC, and ND 1971 Edition with Winter 1972 Addenda.

A.3 ASME Boiler and Pressure Vessel Code, Section III, Subsections NB, NC, and ND 1971 Edition with Summer 1971 Addenda.

A.4 USAS B31.7 - 1969 Edition and "Nuclear Power Piping," with Addenda through Summer 1971.

A.5 ANSI B31.1 - 1973, with all Addenda through and including Summer 1974.

A.6 ANSI B31.1 - 1973, through Summer Addenda B31.1b - 1973.

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

A.8 USAS B31.1.0-1967.

A.9 USAS B31.1.0-1967 and Addenda ANSI B31.7b - 1971.

A.9a USAS B31.1.0-1967 and Addenda ANSI B31.7b - 1973 to ANSI B31.1 -1973.

A.10 ASME Section XI, IWB-3000, 1986 Edition, without Addenda.

A.11 ASME Section XI, 1980 Edition with Winter 1981 Addenda.

A.12 ASME Section XI, 1977 Edition through Summer 1979 Addenda.

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A.14 EPRI Report No. NP-5911 SP & M,"Acceptance Criteria for Structural Evaluation of Erosion/Corrosion Thinning in Carbon Steel Piping," Structural Integrity Associates, San Jose, CA, July 1988.

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

a	Maximum depth of surface flaw, inch
a_f	Final flaw size, inch
A	Corrosion allowance, inch (includes any additional wall thickness for general loss)
A_1	Area of wall thinning that exceeds t_m, inch^2
A_2	Compensating area for local wall thinning, inch^2
A_i	Internal Area of pipe, in^2
α	Coefficient of thermal expansion of pipe;
	Maximum cone angle at the center of the reducer, degrees
B_1, B_2	Primary stress indices
β	Angle to neutral axis of flawed pipe, radians
c	Half length of surface flaw, inch
CVN	Charpy V-notched absorbed energy, ft-lb
d_1, d_2	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_{cg}	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_1	Outside diameter at the large end of the reducer, inch
D_2	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

F_b	A parameter for circumferential flaw bending stress intensity factor
F_m	A parameter for circumferential flaw membrane stress intensity factor
FAC	Flow Accelerated Corrosion
Flaw	Generic term used to describe cracking or locally thinned area of a pipe wall
GTAW	Gas Tungsten Arc Welding
GMAW	Gas Metal Arc Welding
i	Code stress intensification factor, $0.75i \leq 1$
I_M	Predicted minimum centroidal moment of inertia at the pipe section, in^4
J_{Ic}	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
J_{1mm}	Measure of fracture toughness at 1 mm of crack growth at upper shelf temperature, in-lb/in^2
K_{Ia}	Applied Fracture Toughness, ksi $\sqrt{in}$
K_{Ib}	Mode I stress intensity factor for bending loading, ksi $\sqrt{in}$.
K_{Ic}	Critical Fracture Toughness, ksi $\sqrt{in}$
K'_r	A component of the screening criterion (SC), the ratio of the stress intensity factor to material toughness
K_{Im}	Mode I stress intensity factor for membrane loading, ksi $\sqrt{in}$.
l_f	Total flaw length, inch
L	Length of locally thinned area less than t_n, inch
L_m	Maximum length of thinned area less than t_m, inch
$L_{m(a)}$	Axial length of locally thinned area less than t_m, inch
$L_{m(t)}$	Tangential (transverse) length of locally thinned area in less than t_m, inch
$L_{m,min}$	Minimum L_m measured, inch
L_a	Length of reinforcement area, inch
M_σ	Margin of stress
M_A	Resultant moment loading due to weight and other sustained loads, in-1b
M_B	Resultant loading moment due to occasional load, in-lb
M_C	Range of resultant moment due to thermal expansion, in-lb
MIC	Microbiologically Induced Corrosion
N	Number of cycles
P	Internal (or external) design pressure, psi

	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_1	Ratio of Z_n to Z_1
R_2	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_{min}	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_c	Basic material allowable stress at cold temperature, psi
SC	Screening Criterion
SE	Maximum allowable stress in material due to internal presure 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

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
σ	bending stress at the flawed location for dead weight, pressure, thermal expansion, and SSE as used in GL 90-05, psi
σ_b	Reference bending stress at the limit load, psi
σ_u	Material ultimate strength, psi
σ_y	Material yield stress, psi
σ_{yt}	Material yield stress at temperature, psi
t	Nominal pipe wall thickness, inch
t_{aloc}	Allowable local wall thickness, inch
t_{ap}	Average projected thickness remote from flaw location, inch
t_b	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_M	Larger of t_m and t_{min}, inch
$t_{m,1}$	t_m for large end of reducer, inch
$t_{m,2}$	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
$T_a(T_b)$	Range of temperature on side a(b) of gross structural discontinuity or material discontinuity, °F (see ASME Section III NB 3653)
θ	One-half of the final flaw angle, radian
ν	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, $inch^3$
Z_M	Predicted minimum section modulus for the thinned section, $inch^3$

Z_n Section modulus based on nominal wall thickness t_n, inch^3

Attachment III: Inputs / Requirements Common For Pipe Wall Thinning and Crack-Like Flaw Evaluation

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

Component or Subcomponent Location:	
Location: Plant System	
Location: Building	
Location: Elevation	
Location: Other Details, if any	
Piping or Component:	
Description: Pipe / Branch / Tee / Elbow / Reducer or other	
Line Class: ASME Class 1, 2, 3 or ANSI B31.1 ANSI B31.7 Class 1, 2, 3 or	
Section XI Line Class: Class 1, 2, 3 Non-Safety	
Iso Drawing No.	
P&ID or Other Id No.	
Stress Problem No.	
Line No.	
Node No(s) Used In the Stress Math Model	
Type of Piping: CS / SS	
Component Identification No.	

Table 2: Other Piping Related Information Required for Localized Pipe Wall Thinning and Crack-Like Flaw Evaluation:

Material Ultimate Strength (σ_u) psi	
Material Yield Stress (σ_y) psi	
Material Yield Stress at Temperature (σ_{yt}) psi	
Modulus of Elasticity (E) psi	
Modulus of Elasticity at Room Temperature (E_c) psi	
Modulus of Elasticity at Pipe Temperature (E_t) psi	
Coefficient of Thermal Expansion of Pipe Material over a range from 70^0F to Temperature (α)	
Poisson's Ratio (ν) at all Temperatures	
Applied Fracture Toughness (K_{Ia}) ksi$\sqrt{in}$	*
Critical Fracture Toughness (K_{Ic}) ksi$\sqrt{in}$	*

* Information required for Fracture Mechanics Evaluation of Crack-like Flaws

Table 3: Material and Geometry of the Pipe and Description of Weld:

Material of Pipe	
Specification	
Type or Grade	
Class	
Product Form	
Geometry of Pipe	
Nominal diameter (d) inch	
Schedule	
Pipe O.D. (D_0) inch	
Nominal thickness (t) inch	
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:

PIPING PRESSURES (psi):	
Normal Operating (P_n)	
Maximum Operating (P_O)	
Internal Design (P)	
External Design, if applicable (P) (eg., Condenser Lines)	
PIPING TEMPERATURES (^{o}F):	
Operating	
Maximum Operating	
Design (T)	
HIGH ENERGY PIPING CONSIDERATIONS	
Is Piping High Energy (T > 200°F and P > 275 psig) or Moderate Energy (T ≤ 200°F or P ≤ 275 psig)	
SEISMIC CATEGORY: (I, II, II/I, III)	
RESULTANT MOMENT LOADINGS (in-lb) **(For Class 2 & 3 and B31.1) *** Due to Weight and Other Sustained Loads (M_A) Due to Occasional Loads (M_B) 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.

Attachment 7.9: Informational Attachment
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Table 5: Design Allowables:

ALLOWABLE PIPING STRESSES (psi):	
Class 1 and B31.7 Piping:	
Design Stress Intensity (S_m) at Design / Operating Temperature	
Class 2, 3 and B 31.1 Piping	
Maximum Allowable Stress at Design Temperature in Code Hoop Stress Equations (S)	
Basic Material Stress at Cold Temperature (S_c)	
Basic Material Allowable Stress at Design (hot) Temperature (S_h) in Code Stress Equations 8, 9 and 11	
Allowable Stress Range for Expansion Stress (S_A) in Code Stress Equations 10 and 11	
Weld Joint Efficiency (E)	*

* Required For Pipe Wall Thinning (Indication) Evaluation

Attachment 7.9: Informational Attachment
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Table 6: Applicable Codes for the Evaluation of Indications and Flaws:

PLANT:	Ref. No.	CODE	Check Applicable Code
ANO-1	A.4	USAS B31.7 - 1969 Piping Classes I, II, and III with Addenda through Summer 1971 (Per Piping Spec: ANSI B31.7c - 1971, ASME - 71 Winter 1972 Addenda)	
ANO-1	A.9a	USAS B31.1.0 - 1967 (Per Piping Spec: ANSI B31.1b - 1973 to ANSI B31.1 - 1973).	
ANO-1	A.11 A.10	ISI: ASME Section XI, 1980 Ed. with Winter 1981 Addenda. Repair & Replacement: ASME Section XI, 1986 Ed. w/o Addenda	
ANO-2	A.3	ASME Boiler and Pressure Vessel Code, Section III, Subsections NB, NC, ND 1971 with Summer 1971 Addenda	
ANO-2	A.9	USAS B31.1.0 - 1967 and Addenda ANSI B31.1 b - 1971	
ANO-2	A.10	ISI: ASME Section XI, 1986 Ed. w/o Addenda. Repair & Replacements: ASME Section XI, 1986 Ed. w/o Addenda.	
GGNS	A.1	ASME Boiler and Pressure Vessel Code, Section III, Subsections NB, NC, ND 1974, through Summer 1975 Addenda.	
GGNS	A.7	ANSI B31.1 - 1973 , through Winter 1973 Addenda	
GGNS	A.12	ASME Section XI, 1977 Ed. through Summer 1979 Addenda	
RBS	A.1	ASME Boiler and Pressure Vessel Code, Section III, Subsections NB, NC, ND 1974, through Summer 1975 Addenda.	
RBS	A.5	ANSI B31.1 - 1973 , through Summer 1974 Addenda	
RBS	A.11	ASME Section XI, 1980 Ed. through Winter 1981 Addenda	
W-3	A.1	ASME Boiler and Pressure Vessel Code, Section III, Subsection NB 1974, with Summer 1975 Addenda.	
W-3	A.2	ASME Boiler and Pressure Vessel Code, Section III, Subsections NC, ND 1971 with Winter 1972 Addenda.	
W-3	A.5	ANSI B31.1 - 1973 , with All Addenda through and including Summer 1974	
W-3	A.11	ASME Section XI, 1980 Ed. with Winter 1981 Addenda.	

Attachment IV: Inputs / Requirements for Evaluation of Pipe Wall Thinning

Table 1: Description of Locally Thinned Area:

Define Initiating Mechanism:	
Corrosion Mechanisms such as: (1) Flow Accelerated Corrosion (FAC) (2) Microbilogically Induced Corrosion (MIC), Solid Particle Impingement & Fouling in SSW (3) Cavitation & Flashing Downstream of Orifices, Flow Control Valves And Level Control Valves (4) Mechanical Abrasion, Manufacturing Process, Pipe Wall Grinding, and (5) Environmental Conditions.	
Geometry of Locally Thinned Area: (see Figure 1)	
Internal or External	
Minimum Projected Wall Thickness (t_p), inch	
Length of Locally Thinned Area Less Than t_n (L), inch	
Maximum Length of Thinned Area Less Than t_m (L_m), inch	
Axial Length of Locally Thinned Area Less than t_m, $L_{m(a)}$ inch	
Tangential (transverse) Length of Locally Thinned Area Less Than t_m, $L_{m(t)}$ inch	

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 ±R in the axial direction and shall include all of the thinned location in the circumferential direction.

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

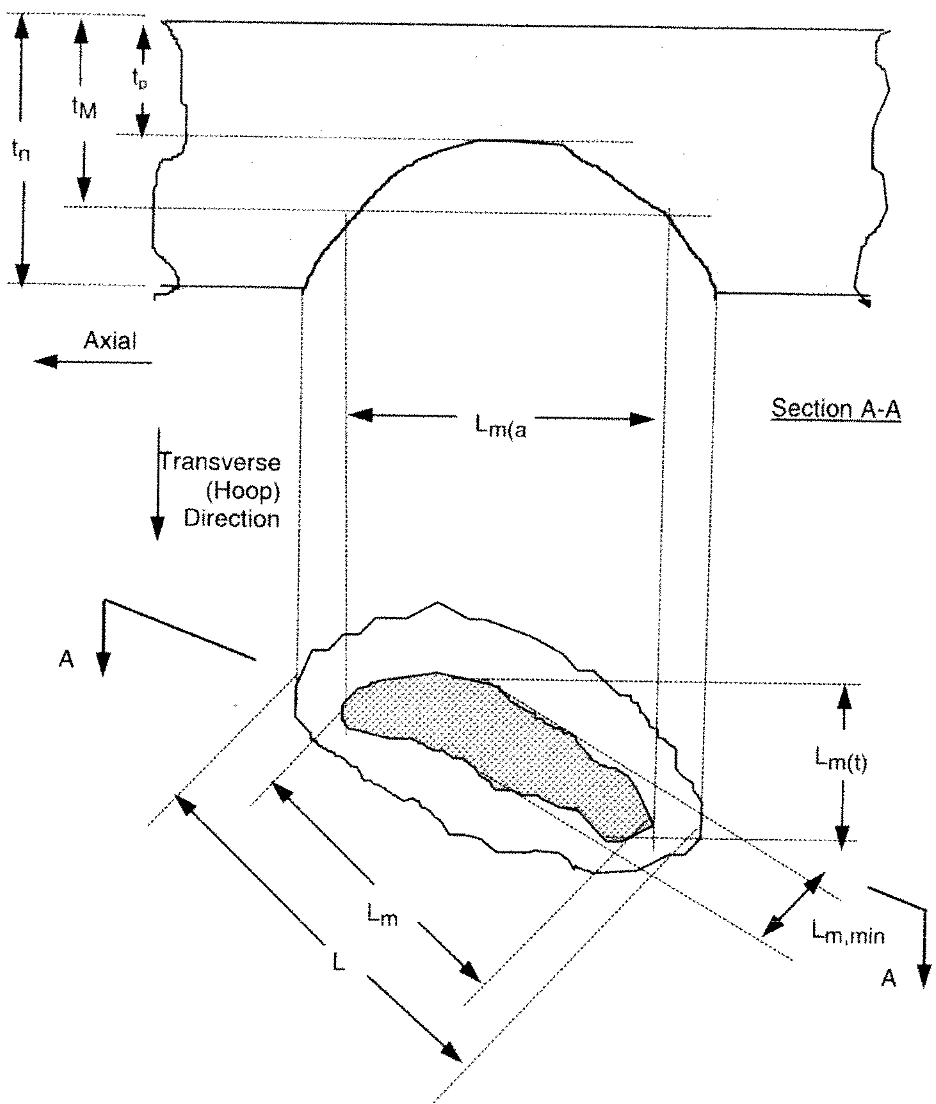

Figure 1: Local Pipe Wall Thinning Parameters

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

Table 1:Description of the Flaw Location:

Define Initiating Mechanism:	
Fatigue / SCC / FAC / MIC / Other such as Mechanical abrasion, Manufacturing process, Pipe wall surface grinding, Environmental conditions or Other	
Geometry of Flaw Location:	
Pipe OD (D_o), inch	
Nominal Pipe Wall Thickness (t), inch	
Flaw Orientation	
Flaw Length (l_f), inch	
Maximum Flaw Depth for Surface Flaws (a), inch Maximum Flaw Depth for Subsurface Flaws (2a), inch	

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 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).

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

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_n 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_1) is equal to (t_m- t_p)L_m. Depending on the shape of the locally thinned area, the true value of A_1 may be significantly less than this. In addition, the area available for reinforcement, A_2, 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.

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.

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

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 $1.0(Rt_n)^{0.5}$. For application to locally thinned pipes, the meridional direction is axial to the pipe, and t is t_n. 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 $2.5(Rt_n)^{0.5}$. 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 $PD_o/2t$ 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 $D_oM_i/2I$ 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.

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

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 ΔT_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 ΔT_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 ΔT_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 ΔT_2 should be taken from the original piping evaluation, since the thinned pipe will have actual ΔT_2 < the original ΔT_2. The pressure and M_i 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 $1.5S_m$. For the axial stresses due to internal pressure and primary bending moments, the $PD_o/4t_n$, M_A/Z and $(M_A + M_B)/Z$ 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.

Attachment 7.9: Informational Attachment

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

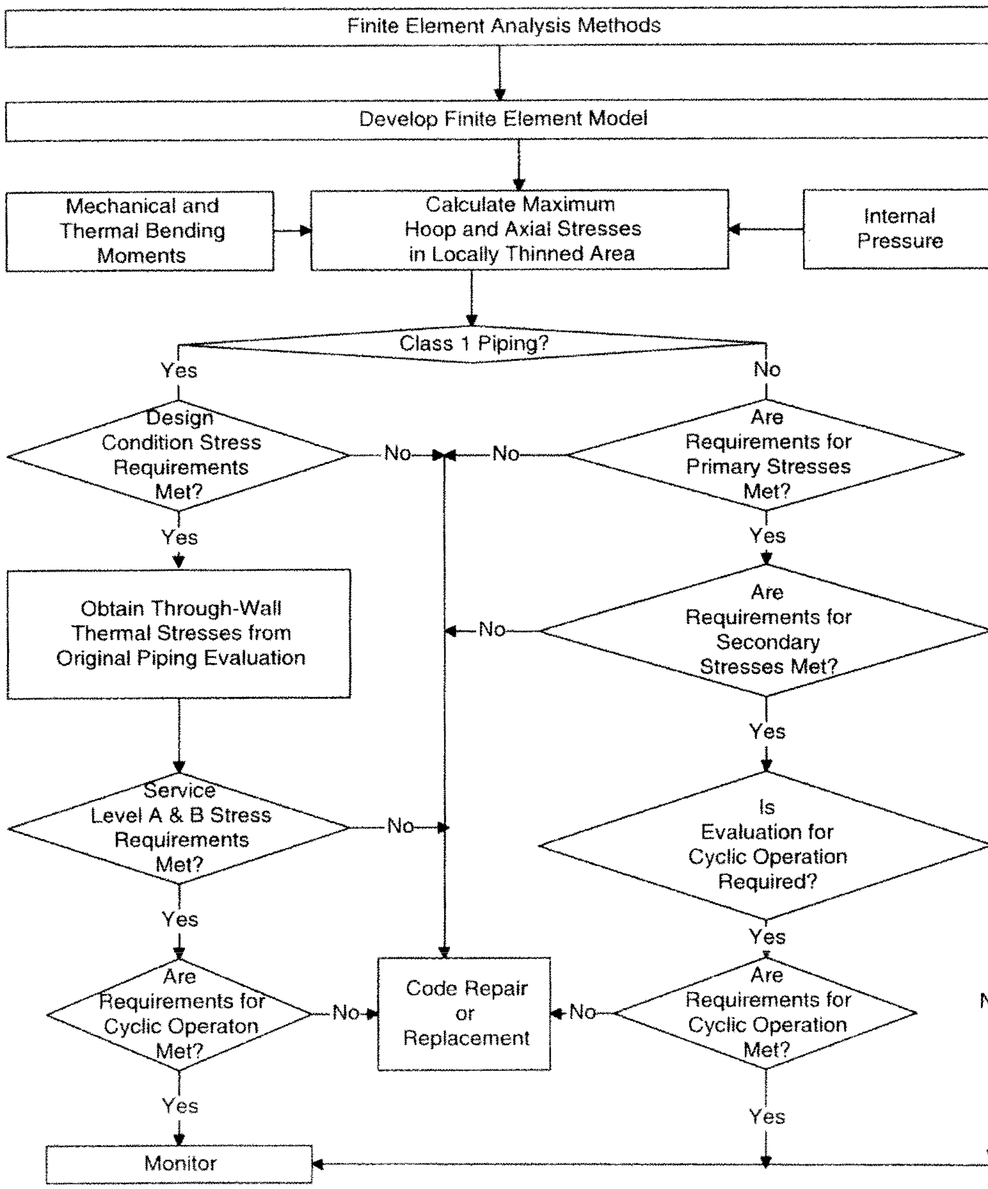
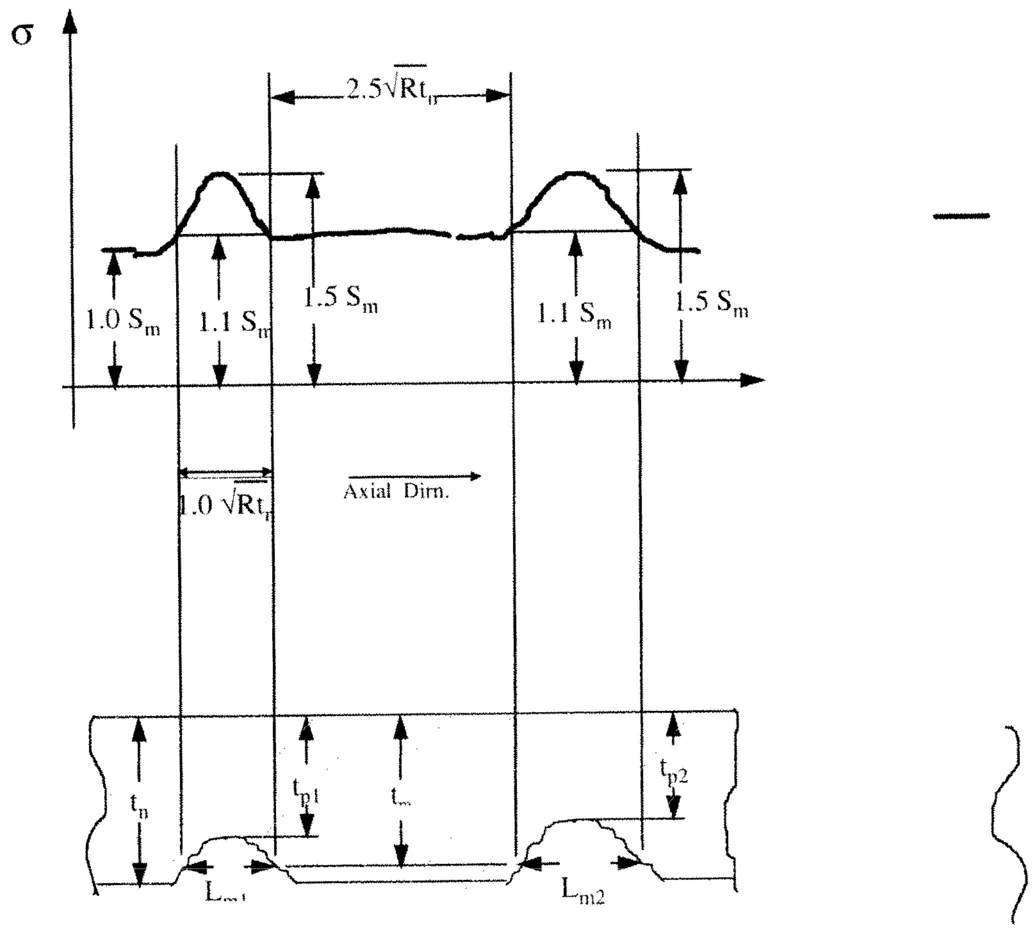


Figure 1: Finite Element Analysis Method



$L_{mavg} = (L_{m1} + L_{m2})/2$

L_{mm} = Larger of L_{m1}, L_{m2}

Figure 2: Illustration of Local Primary Membrane Stress

Attachment XI: CLFE: Section XI Flaw Evaluation Standards.

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 inservice 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 mechancis 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,....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, $2d_{max}$, 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 $2d_{max}$, 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 inservice 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 $0.4a \leq S \leq a$, 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/l = 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/l = 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/l = 0.019 (between 0.0 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 $2d_l$. Thus the combined depth, 2d, 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/t_{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 100^0 F)

a/l	t = 0.312 in.		t = 1.0 in.		t = 2.0 in.		t = 3.0 in.	
	surface	subsurf.	surface	subsurf.	surface	subsurf.	surface	subsurf.
0.00	11.1	13.8Y	10.0	12.6Y	8.5	10.8Y	7.0	8.7Y
0.05	11.8	14.4Y	10.8	13.0Y	9.3	11.2Y	7.5	9.1Y
0.10	13.0	15.6Y	11.8	14.2Y	10.2	12.1Y	8.2	9.9Y
0.15	14.4	17.2Y	13.2	15.7Y	11.2	13.5Y	9.1	10.9Y
0.20	14.4	17.2Y	14.8	17.7Y	12.6	15.1Y	10.3	12.3Y
0.25	14.4	17.2Y	14.8	17.7Y	14.2	17.1Y	11.7	13.9Y
0.30	14.4	17.2Y	14.8	17.7Y	14.2	17.1Y	13.2	15.7Y
0.35	14.4	17.2Y	14.8	17.7Y	14.2	17.1Y	13.2	17.7Y
0.40	14.4	17.2Y	14.8	17.7Y	14.2	17.1Y	13.2	17.7Y
0.45	14.4	17.2Y	14.8	17.7Y	14.2	17.1Y	13.2	17.7Y
0.50	14.4	17.2Y	14.8	17.7Y	14.2	17.1Y	13.2	17.7Y

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)

a/l	t = 0.312 in.		t = 1.0 in.		t = 2.0 in.		t = 3.0 in.	
	surface	subsurf.	surface	subsurf.	surface	subsurf.	surface	subsurf.
0.00	11.7	11.7Y	10.6	10.6Y	10.0	10.0Y	9.5	9.5Y
0.05	12.0	12.0Y	10.7	10.7Y	10.2	10.2Y	9.6	9.6Y
0.10	12.2	12.2Y	11.0	11.0Y	10.4	10.4Y	9.7	9.7Y
0.15	12.4	12.4Y	11.1	11.1Y	10.5	10.5Y	9.9	9.9Y
0.20	12.5	12.5Y	11.4	11.4Y	10.7	10.7Y	10.1	10.1Y
0.25	12.5	12.5Y	11.5	11.5Y	10.9	10.9Y	10.2	10.2Y
0.30	12.5	12.5Y	11.7	11.7Y	11.1	11.1Y	10.4	10.4Y
0.35	12.5	12.5Y	11.9	11.9Y	11.2	11.2Y	10.6	10.6Y
0.40	12.5	12.5Y	12.1	12.1Y	11.4	11.4Y	10.7	10.7Y
0.45	12.5	12.5Y	12.2	12.2Y	11.6	11.6Y	10.9	10.9Y
0.50	12.5	12.5Y	12.5	12.5Y	11.7	11.7Y	11.1	11.1Y

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.)

Nominal Pipe Wall Thickness	Laminar Area sq.in.
0.625 in. & less	1.25 (7.5*)
2.0 in. (3.5" *)	4.0 (7.5*)
6.0 in.	12.0

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.)

Nominal Pipe	Ferritic Steel[1]		Austenitic Steel[2]	
Wall Thickness	Surf.	Subsurf.	Surf.	Subsurf.
0.312 in.	0.1875	0.25	0.2	0.25
1.0 in.	0.3125	0.375	0.25	0.375
2.0 in.	0.625	0.75	0.45	0.75
3.0 in.	0.875	1.2	0.65	1.2
4.0 in.	0.875	1.4	0.65	1.4

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^{0}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.

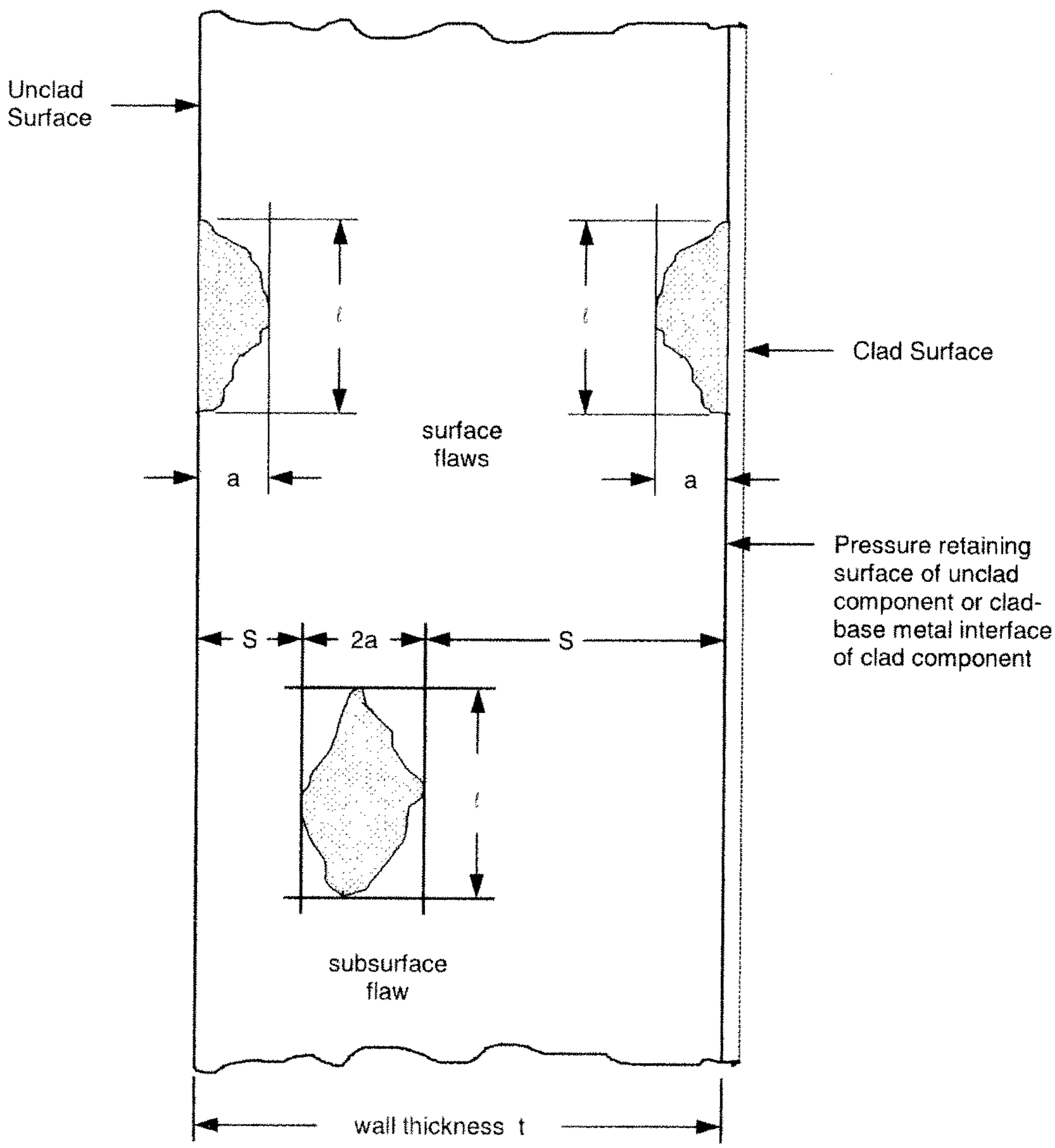


Figure 1 Basic Flaw Sizing Method from ASME Section XI

Source: Ref. A.10 and A.11, Fig. IWA-3310-1.

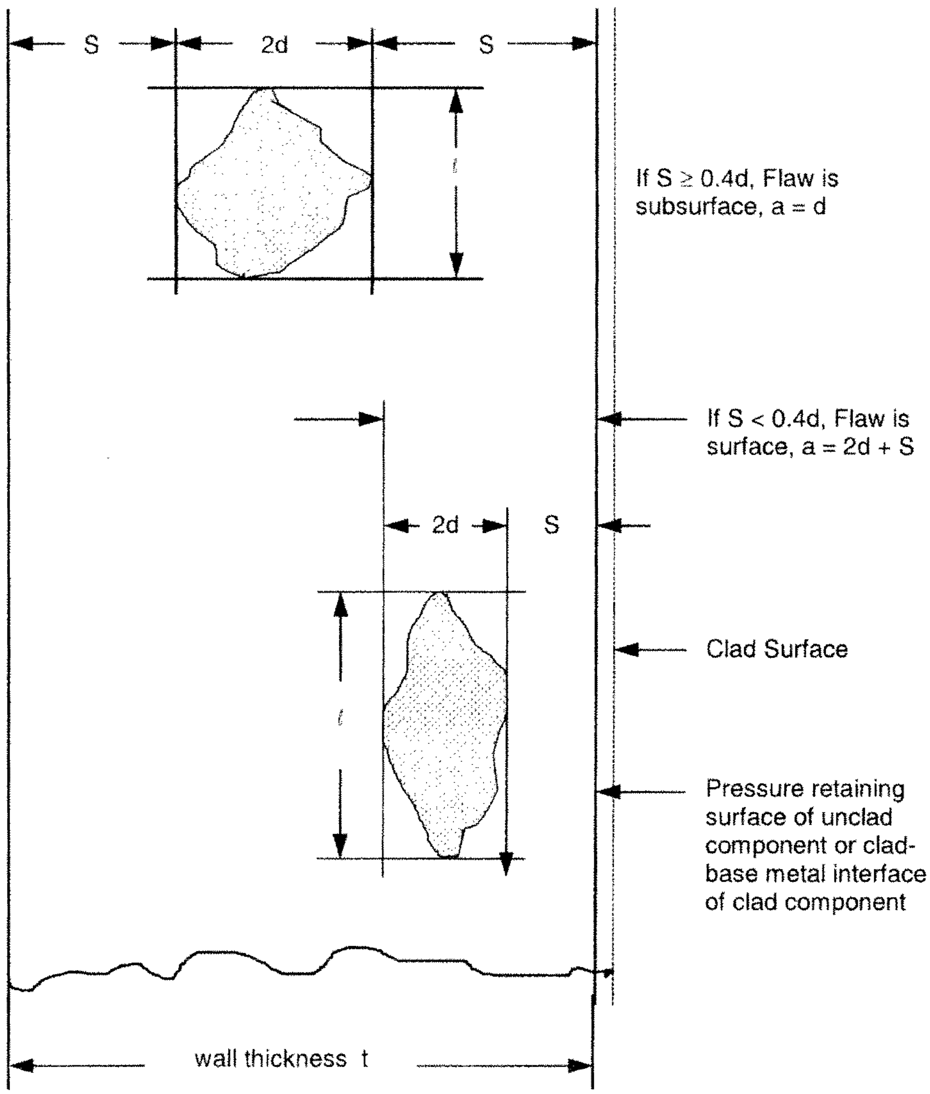


Figure 2 Near-Surface Flaw Proximity Rule from ASME Section XI

Source: Ref. A.10 and A.11, Fig IWA-3310-1 and IWA-3320-1.

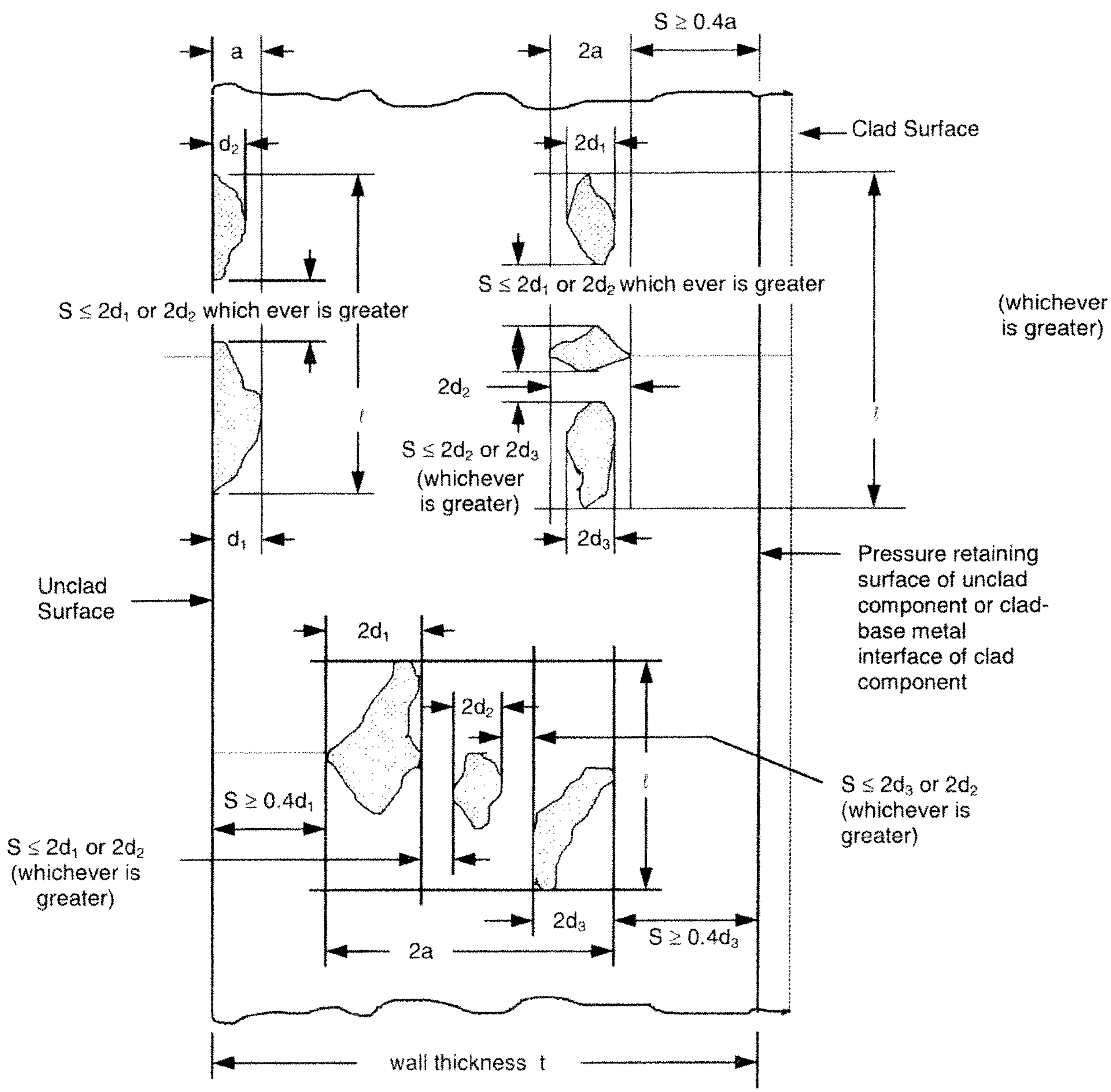
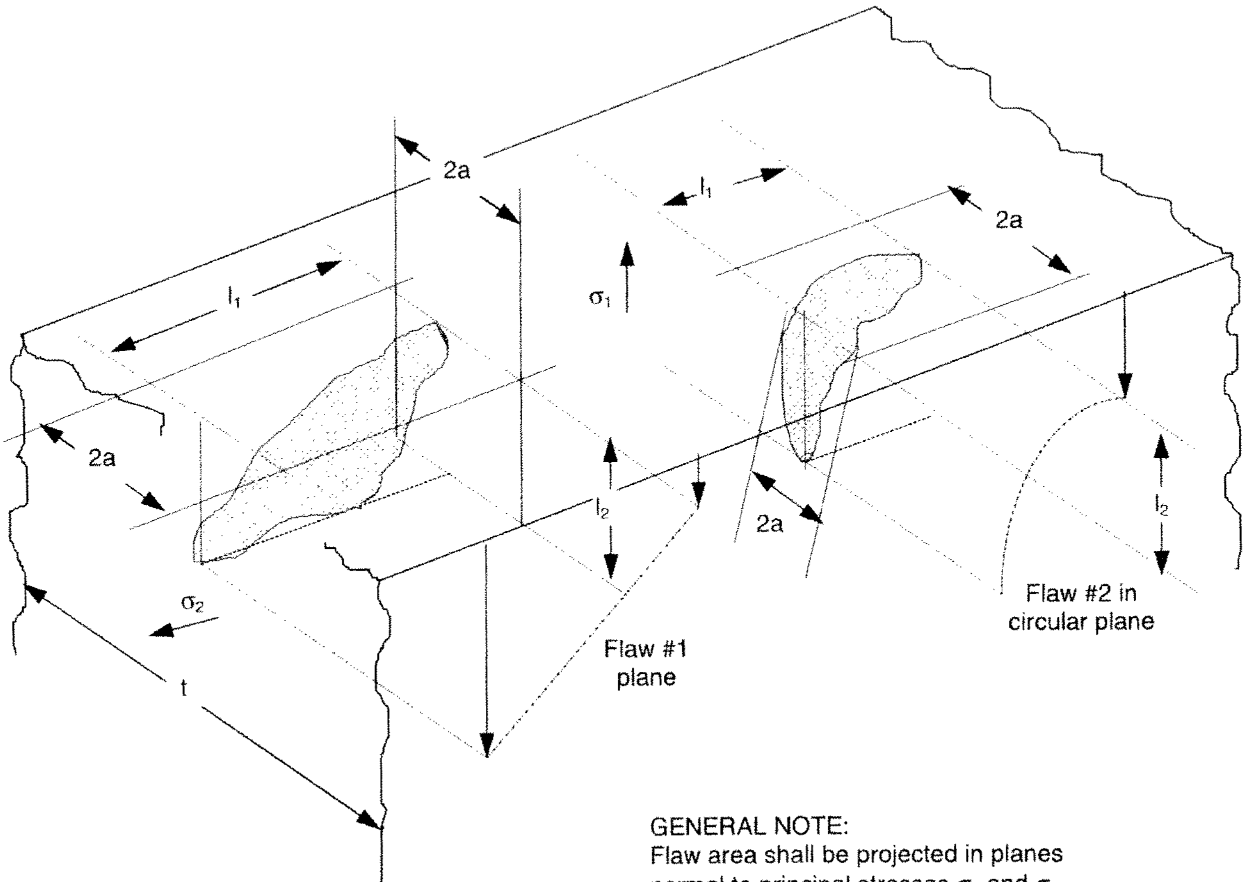


Figure 3 Flaw-to-Flaw Proximity Rule from ASME Section XI

Sourrce: Ref. A.10 and A.11, Figure IWA-3330-1.



GENERAL NOTE:
Flaw area shall be projected in planes normal to principal stresses σ_1 and σ_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.

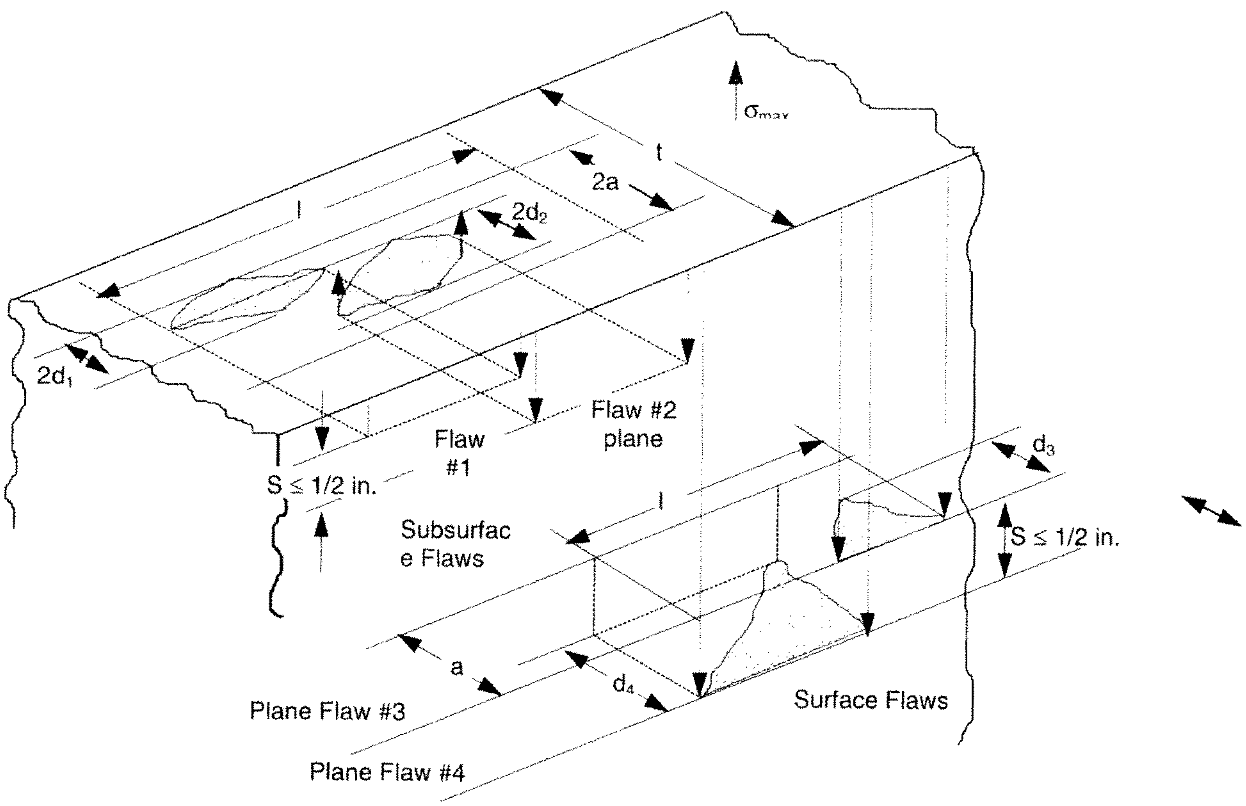


Figure 5: Flaw Sizing Rules for Planar Flaws in Multiple Planes

Source: Ref. A.10 and A.11, Fig. IWA-3350-1.

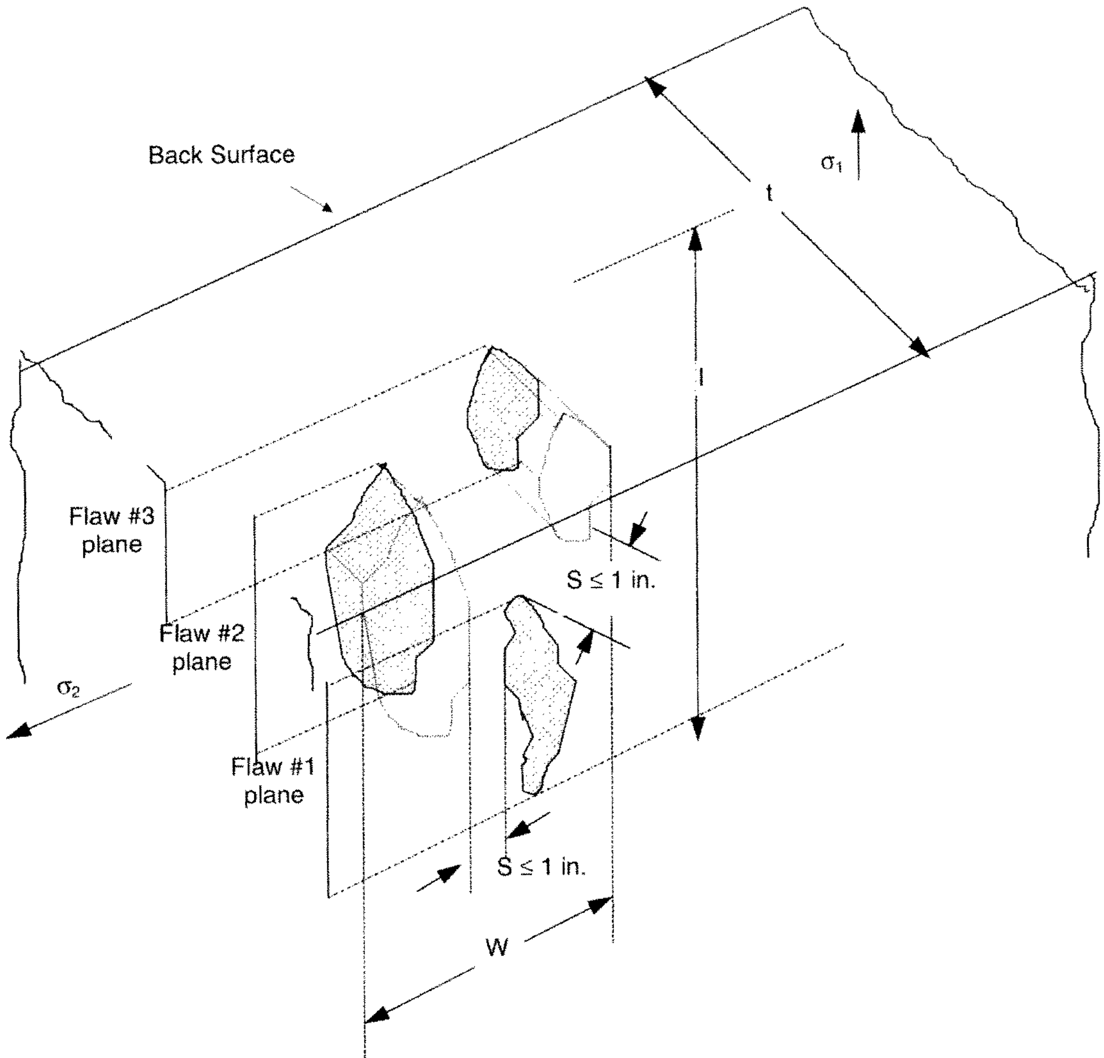


Figure 6: Flaw Sizing Rules for Laminar Flaws in Multiple Planes

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

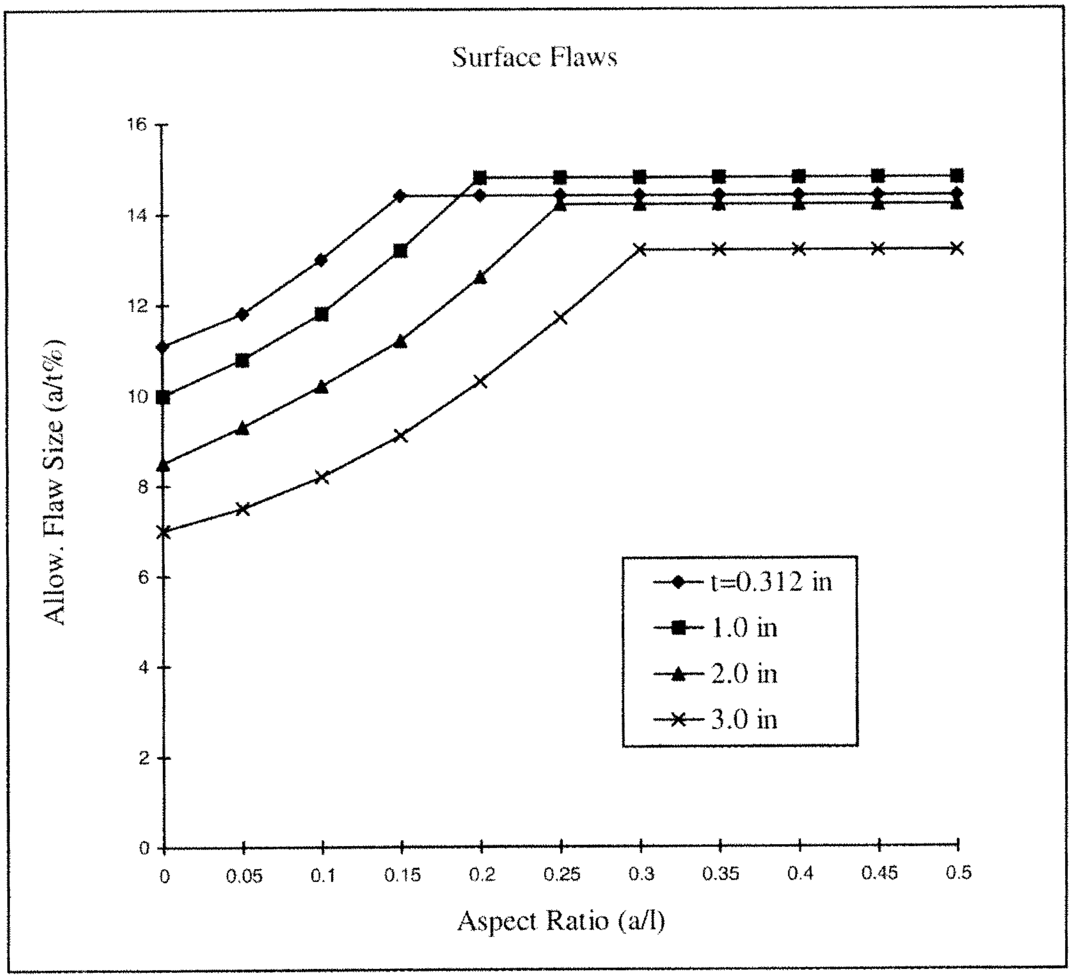


Figure 7A Ferritic Flaw Standards

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

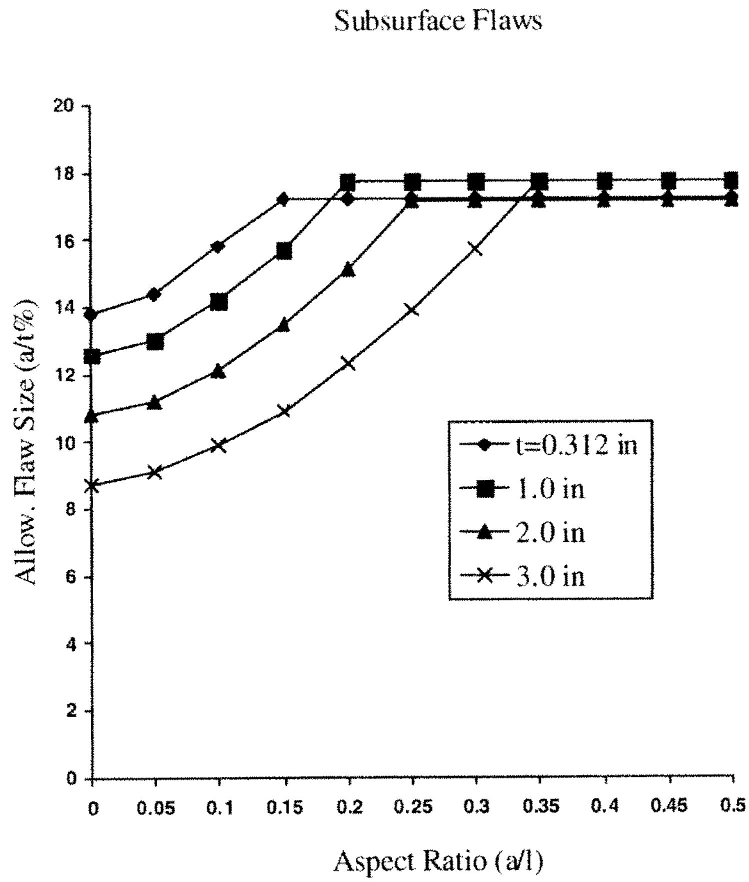


Figure 7B Ferritic Flaw Standards

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

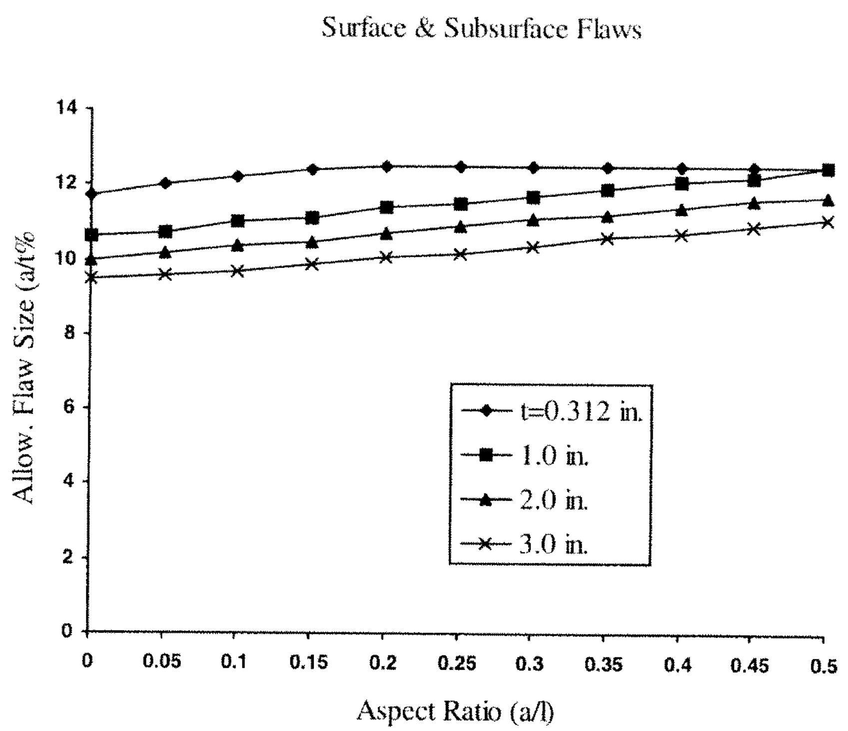


Figure 8 Austenitic Flaw Standards

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

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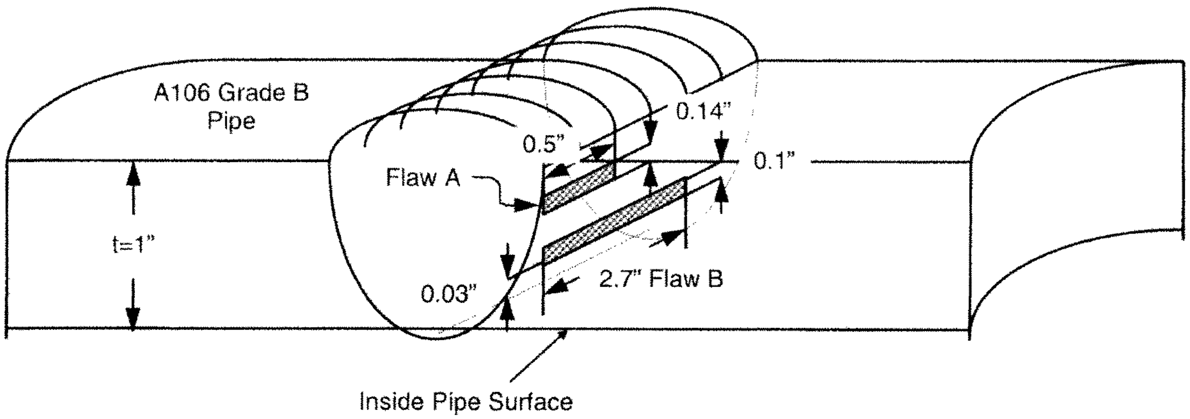

Flaw A (Subsurface)

2a = 0.14"
a = 0.07"
l = 0. 5"
a/l = 0.14"
a/t = 0.07
Allowable a/t = 0.154
(see table 1)
Flaw is acceptable

Flaw B (Subsurface)

2d = 0.1"
d = 0.05"; 0.4d = .02"
S = 0.03"
.4d > S < d; ✧ Subsurface Flaw; ✧ d = a;
✧a = 0.05"
✧ Subsurface Flaw S/a = 0.6 = Y
t = 1"
a/l = 0.019
a/t = 0.05
Allowable a/t = 0.127Y = 0.076
(see table 1)
Flaw is acceptable

Figure 9: Subsurface Flaw Evaluation Examples

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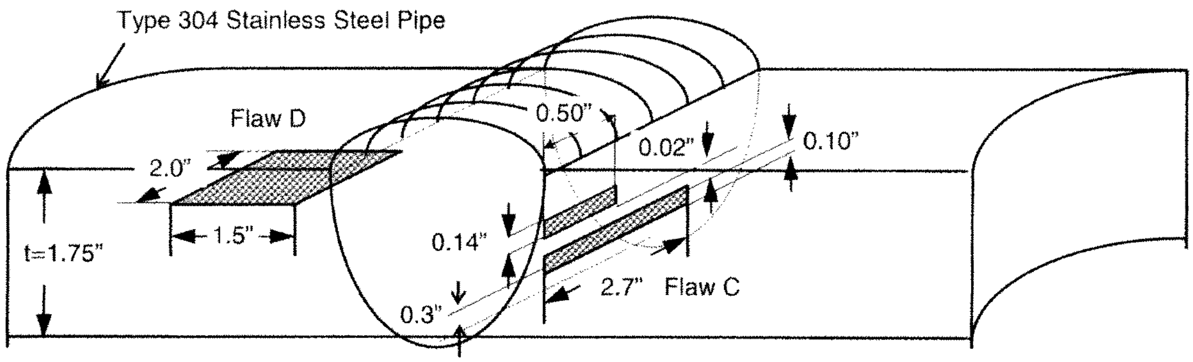

<u>Flaw C (Subsurface)</u>
$2d_1 = 0.14"$; $d_1 = 0.07"$;
$2d_2 = 0.1"$; $d_2 = 0.05"$;
S = 0.02" < $2d_1$ (greater of d_1 and d_2)
2d = 0.26" (=$2d_1$ + $2d_2$ + S)
d = 0.13"
l = 3.2" (=2.7" + 0.5")
S = 0.03" to surface
S/d = 0.231 ⟡ Surface flaw (¤ S<0.4)
a = surface flaw depth = 2d + S = 0.26 + 0.3
a = 0.29"
l = 3.2"
a/l = 0.091
a/t = 0.166
Allowable a/t = 0.105 (from table 2)
<u>Flaw is unacceptable</u>

<u>Flaw D (Near Surface)</u>
Area = 3.0 in^2 (= 2.0 x 1.5)
Allowable Area = 7.5 in^2
<u>Flaw is Acceptable</u>

Figure 10: Surface and Laminar Flaw Evaluation Examples

Attachment XII: CLFE: Procedure for Austenitic Piping

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 (Class3) are used, a prompt reporting has to be submitted for regulatory concurrence. The system, however can be operable until the regulatory approval.

1.6 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 $\sqrt{R_o t}$ from the centerline of a girth butt weld, where R_o 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 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 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_e - Thermal expansion

3.2.2 Level C/D
- Pm - Pressure
- P_b - Deadweight + SSE Seismic
- P_e - 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 α and n, the yield stress σ_o, the flow stress σ_f, Modulus of Elasticity E, and the fracture toughness J_{Ic}. Typical values for SAW and SMAW welds have been provided as follows [A.19]:

Parameter	Submerged arc weld	Shielded metal arc weld
α	11.0	9.0
n	6.9	9.8
σ_o, ksi	33.7	49.4
σ_f, ksi	42.1	55.4
E, ksi	25,000.0	25,000.0
J_{Ic}, in-lb/in^2	650.0	990.0

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_I) 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 USNRCC 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:

$$\frac{da}{dN} = C_o(\Delta K_I)^n \qquad \text{Eqn. 2}$$

where:

$$n = 3.3, \text{ and } C_o = C(S) \qquad \text{Eqn.3}$$

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

$$C = 10^{[-10.009+8.12x10^{-4}T-1.13x10^{-6}T^2+1.02x10^{-9}T^3]} \qquad \text{Eqn. 4}$$

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

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_{min} / K_{max}), and is given by:

S = 1.0	when R ≤ 0
= 1.0 + 1.8R	when 0 < R ≤ 0.79
= -43.35 + 57.97R	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:

$$da / dN = C \cdot E \cdot S(\Delta K)^n \qquad \text{Eqn. 5}$$

where:

da/dN = change in crack depth, a, per fatigue cycle, in/cycle

C, n = material constants

n = 3.3

C = 2×10^{-19}

S = R ratio correction factor = $[1.0 - 0.5R^2]^{-4}$

R = K_{min}/K_{max}

E = environmental factor (equal 1.0, 2.0, and 10.0 for air, PWR, and BWR environments, respectively)

ΔK = $K_{max} - K_{min}$, ksi$\sqrt{(in)}$

K_{min}, K_{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 Unintensified Stresses

8.3.6 Safety Factor = 2.77

8.3.7 Assumes $\sigma_f = 3S_m$

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 Unintensified Stresses

8.4.6 Safety Factor = 1.39

8.4.7 Assumes $\sigma_f = 3S_m$

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 $\sigma_f = 3S_m$

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 $\sigma_f = 3S_m$

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 $\theta + \beta \leq \pi$

$$P_b' = \frac{6S_m}{\pi}\left(2\sin\beta - \frac{a}{t}\sin\theta\right) \quad \text{Eqn. 6}$$

$$\beta = \frac{1}{2}\left(\pi - \frac{a}{t}\theta - \pi\frac{P_m}{3S_m}\right) \quad \text{Eqn. 7}$$

For $\theta + \beta > \pi$

$$P_b' = \frac{6S_m}{\pi}\left(2 - \frac{a}{t}\right)\sin\beta \quad \text{Eqn. 8}$$

$$\beta = \left(\frac{\pi}{2 - \frac{a}{t}}\right)\left(1 - \frac{a}{t} - \frac{P_m}{3S_m}\right) \quad \text{Eqn. 9}$$

where all the terms are shown in Figure 6 and

$$\sigma_f = 3S_m \quad \text{Eqn. 10}$$

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:

$$P_b' = SF(P_m + P_b) - P_m \quad \text{Eqn. 11}$$

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

$$P_b' = Z_1 \cdot SF(P_m + P_b + P_e / SF) - P_m \quad \text{Eqn. 12}$$

$$Z_1 = 1.15\left[1 + 0.013(D - 4)\right] \; for\ SMAW$$
$$= 1.30\left[1 + 0.010(D - 4)\right] \; for\ SAW \quad \text{Eqn. 13}$$

where D is the nominal pipe size, NPS and for NPS ≤ 24 in., use D = 24.

8.13 For axial Part-through Flaws:

$$\sigma_h = \frac{3S_m}{SF}\left[\frac{t/a-1}{t/a-1/M_2}\right] \qquad \text{Eqn. 14}$$

where:

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

σ_h = nominal hoop stress = $PD/2t$

D = nominal outside diameter of the pipe

l_f = total flaw length

a = flaw depth. The flaw depth is limited to 75% of thickness

R = mean radius of the pipe

t = nominal thickness

SF = 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.

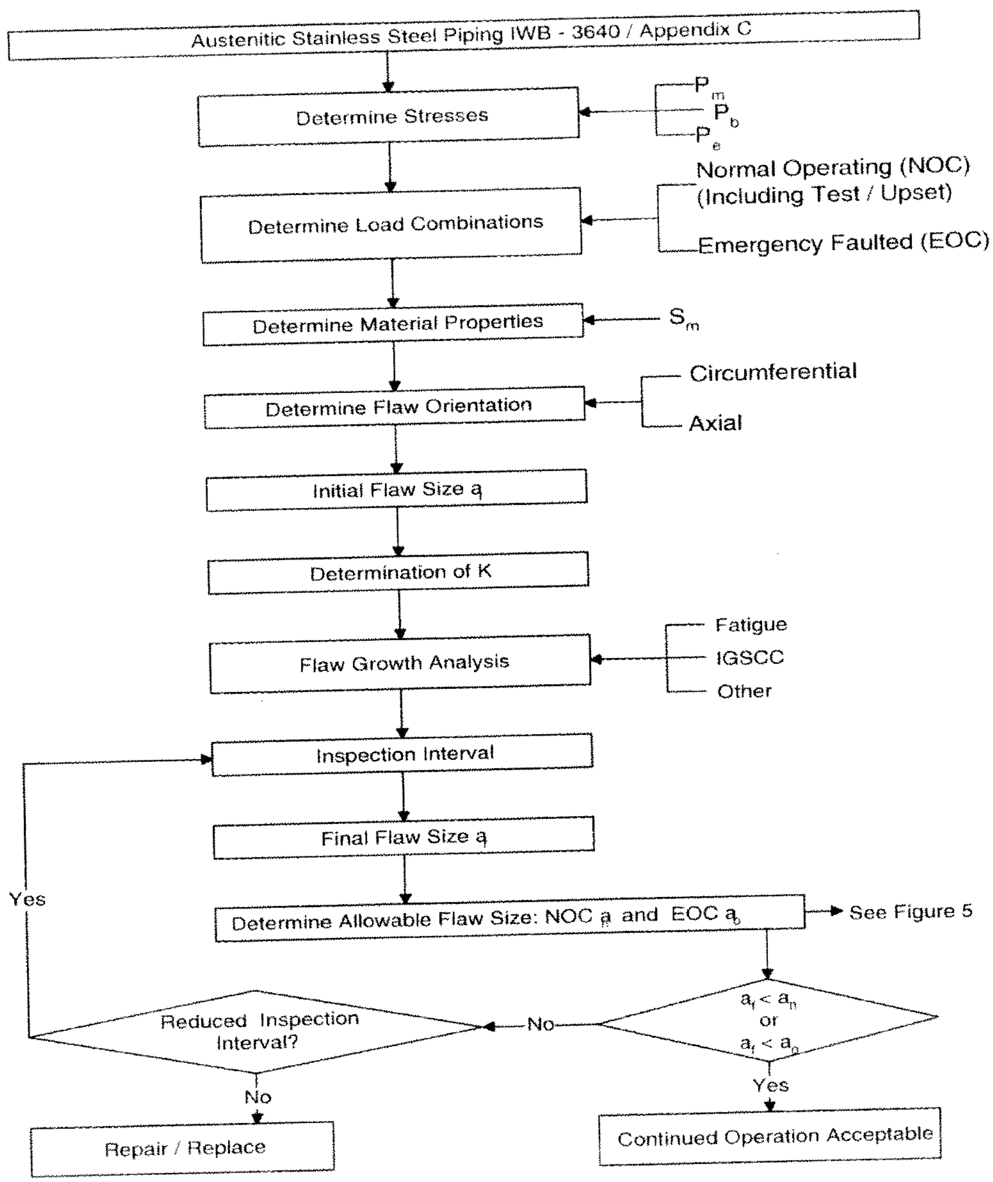

Figure 1: Flaw Evaluation Procedure for Austenitic Steel Piping

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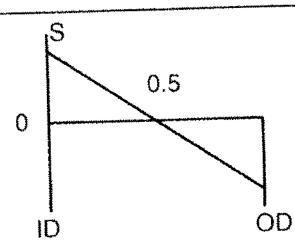
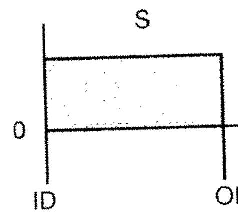
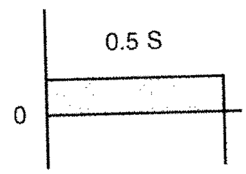
Wall Thickness	Through-Wall Residual Stress [1]	
	Axial	Circumferential [2]
< 1 inch		
≥ 1 inch	See Note 3	

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

Figure 2 Residual Stress Distribution in Large and Small Diameter Piping Welds [A.19, A.21]

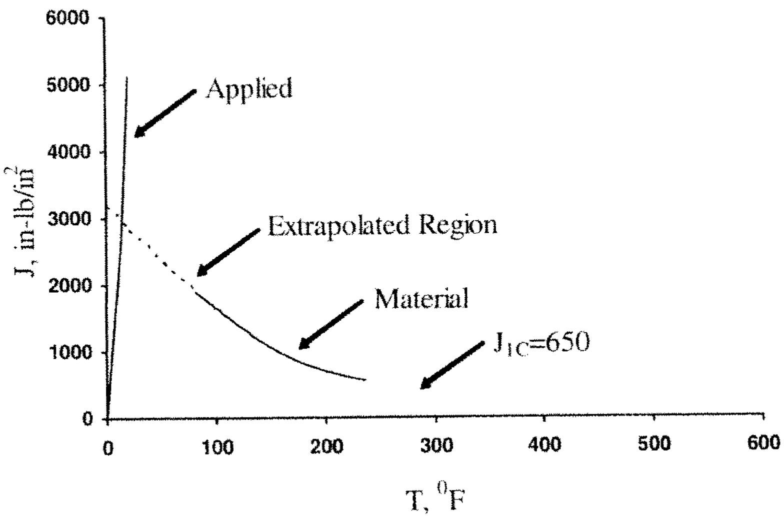


Figure 3: Material J-R Resistance Curve for SAW Weldment at 550⁰ F [A.19]

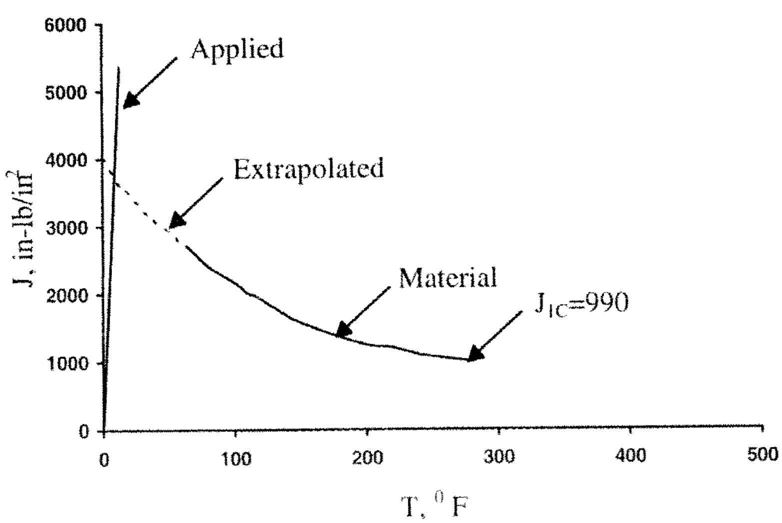


Figure 4 Material J-R Resistance Curve for SMAW Weldment at 550°F [A.19]

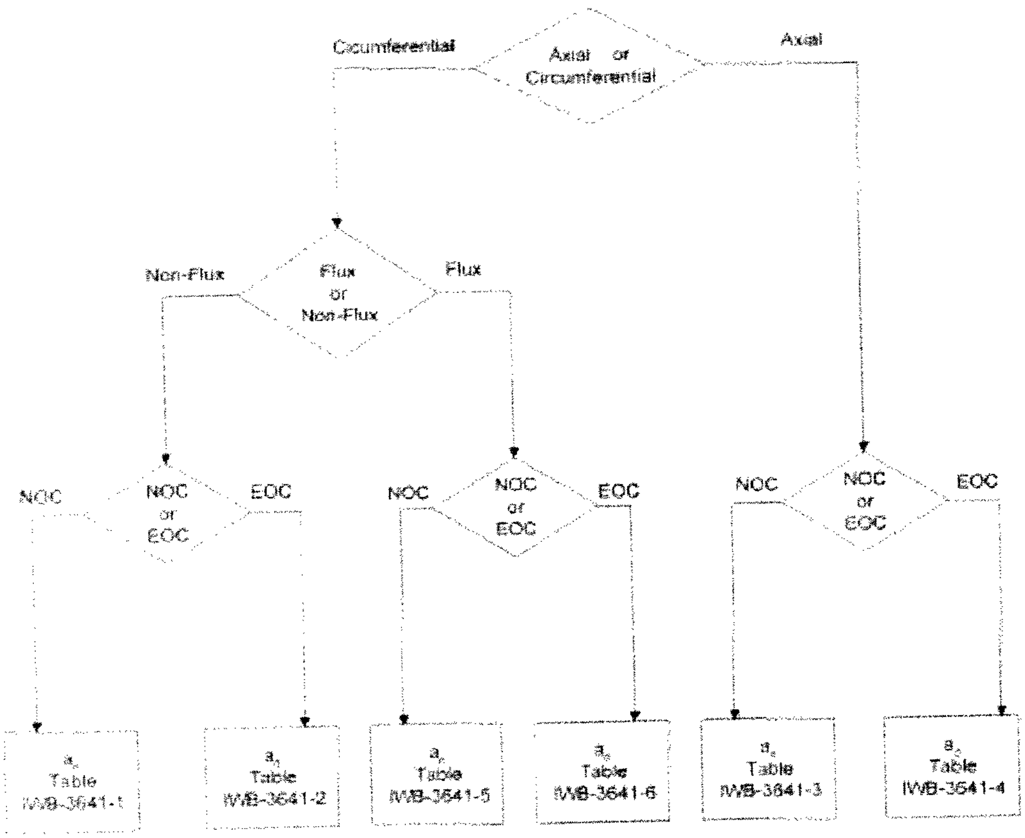
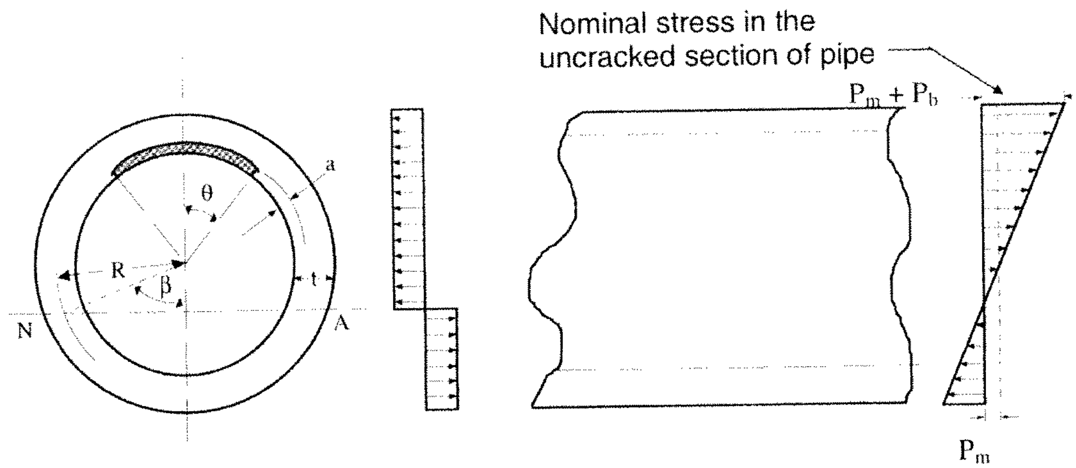


Figure 5: Flow Chart for Allowable Size Determination of Austenitic Stainless Steel Piping



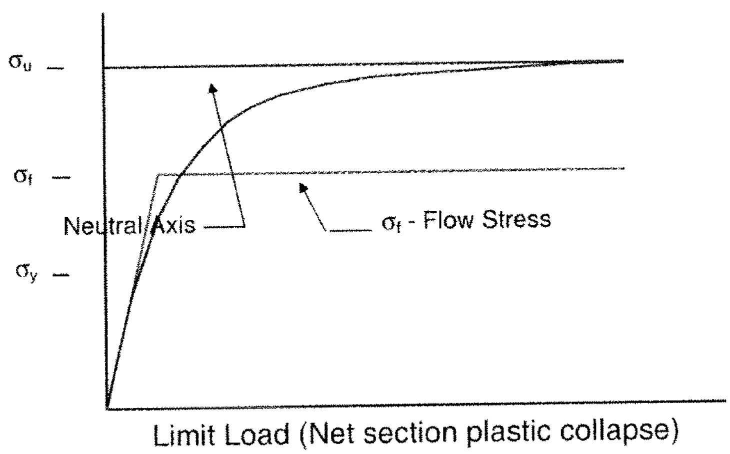


Figure 6: Stress Distribution in a Cracked Pipe -- Basis for Net Section Collapse Criteria for Austenitic Steel Pipe

Attachment XIII: Flaw Evaluation Procedure for Ferritic Piping

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 $\sqrt{R_o t}$ from the centerline of a girth butt weld, where R_o 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]:

$$SC = \left[\frac{K_r'}{S_r'}\right] \qquad \text{Eqn. 1}$$

where:

$$K_r' = \left[\frac{K_I}{K_{Ic}}\right] \qquad \text{Eqn. 2}$$

K_{Ic} = $[J_{Ic} E'/1000]^{.5}$ ksi -√in. Eqn. 3

J_{Ic} = 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' = $[E / (1-v^2)]$ ksi Eqn. 4

where

E = Modulus of Elasticity

v = Poisson Ratio

K_I = Total applied stress intensity factor (as defined in sections 7.4.1 and 7.4.2 for circumferential and axial flaws) ksi -√in

For circumferential flaws, (see section 7.4.1):

$$S_r' = \left[\frac{\sigma}{\sigma_{b,l}}\right] \qquad \text{Eqn. 5}$$

where:

$$\sigma = P_{\text{primary bending}} + P_{\text{expansion}} \qquad \text{Eqn. 6a}$$

$$\sigma_{b,l} = \text{bending stress at limit load} \qquad \text{Eqn. 6b}$$

For axial flaws, (see section 7.4.2):

$$S_r' = \left[\frac{\sigma}{\sigma_l}\right] \qquad \text{Eqn. 7}$$

where:

$$\sigma = P_{\text{axial stress}} \qquad \text{Eqn. 7a}$$

$$\sigma_l = \text{reference stress at limit load} \qquad \text{Eqn. 7b}$$

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	P_m	-	Pressure
	P_b	-	Deadweight + OBE Seismic
	P_e	-	Thermal expansion
3.2.2 Level C/D	P_m	-	Pressure
	P_b	-	Deadweight + SSE Seismic
	P_e	-	Thermal expansion

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, σ_y

Ultimate Strength, σ_u

Young's Modulus, E

Poisson Ratio, ν

Design Stress Intensity, S_m

Fracture Toughness, J_{Ic}

4.3 The values of σ_y, σ_u, E, and S_m are provided in Appendix I of ASME Section III [A.38]. The value of ν is typically taken as 0.3. Minimum values of J_{Ic} are provided in ASME Section XI Appendix H if actual values are not available for the evaluation. J_{Ic} shall be obtained directly from heat-specific J_{Ic} 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:

$$J_{1mm} = 10\,CVN \qquad \text{Eqn. 8}$$

where,

J_{1mm} is flaw extension in in-lb/in^2 and

CVN is heat specific energy in ft-lb units.

Note that the operating temperature is considered as greater than 200^0 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 α and n, and reference stress σ_0. 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.

Parameter	Submerged arc weld
α	2.51
n	4.2
σ_0, ksi	27.1

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 $\theta + \beta \leq \pi$

$$P_b' = \frac{2\sigma_f}{\pi}\left(2\sin\beta - \frac{a}{t}\sin\theta\right) \qquad \text{Eqn. 9}$$

$$\beta = \frac{1}{2}\left(\pi - \frac{a}{t}\theta - \pi\frac{P_m}{\sigma_f}\right) \qquad \text{Eqn. 10}$$

For $\theta + \beta > \pi$

$$P_b' = \frac{2\sigma_f}{\pi}\left(2 - \frac{a}{t}\right)\sin\beta \qquad \text{Eqn. 11}$$

$$\beta = \frac{\pi}{2 - a/t}\left(1 - \frac{a}{t} - \frac{P_m}{\sigma_f}\right) \qquad \text{Eqn. 12}$$

where all the terms are shown in Figure 9 and σ_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 $P_b/P_m \geq 1.0$ 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_c is given as:

$$S_c = \frac{P_b'}{(SF)} - P_m\left[1 - \frac{1}{(SF)}\right] \qquad \text{Eqn. 13}$$

where:

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]

$$\sigma_h = \frac{\sigma_f}{SF}\left[\frac{t/a - 1}{t/a - 1/M_2}\right] \qquad \text{Eqn. 14}$$

where:

$$M_2 = \left[1 + 1.61l^2 / (4Rt)\right]^{1/2} \qquad \text{Eqn. 15}$$

σ_f = $2.4S_m$

σ_h = nominal hoop stress = $PD/2t$

D = nominal outside diameter of the pipe

l = total flaw length

a = flaw depth

R = mean radius of the pipe

t = nominal thickness

SF = 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 $l < l_{crit}$ where l_{crit} is determined by the condition for the stability of through-wall flaws $\sigma_h = \sigma_f / M_2$.

7.2.5.6 Note flaw depths a_n and a_o, 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:

[ ] Eqn. 16

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

$$SR = Z(P_m + P_b + P_e / 1.39) / S_m \qquad \text{Eqn. 17}$$

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_c is determined as:

$$S_c = \frac{1}{(SF)}\left(\frac{P_b'}{Z} - P_e\right) - P_m\left(1 - \frac{1}{Z(SF)}\right) \qquad \text{Eqn. 18}$$

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≤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 ≥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_I) and comparing it to allowable stress intensity factor (K_{Ic}).

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

$$K_I = K_{Im} + K_{Ib} + K_{Ir} \le K_{Ic} \qquad \text{Eqn. 19}$$

where:

$K_{Ic} = [J_{Ic} E'/1000]^{.5}$ ksi $\sqrt{in}$ Eqn. 3

J_{Ic} = 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

$E' = [E / (1-\nu^2)]$ ksi Eqn. 4

$K_{Im} = (SF)\cdot[\sigma](\pi a)^{0.5} F_m$ ksi$\sqrt{in}$ Eqn. 20

where,

$$\sigma = P_m = \frac{P}{2\pi Rt} \text{ ksi}$$ Eqn. 21

where

P = Total axial load on pipe including pressure, kips

$$K_{Ib} = \left[(SF)\{M/(\pi R^2 t)\} + P_e\right](\pi a)^{0.5} F_b$$
$$= \left[SF\{\sigma_b\} + \sigma_e\right](\pi a)^{0.5} F_b \quad \text{ksi } \sqrt{in}$$ Eqn. 22

K_{Ir} = stress intensity factor due to residual stress with a safety factor of 1.0, ksi $\sqrt{in}$

K_I = total applied stress intensity factor, ksi $\sqrt{in}$

$F_m = 1.10 + x\,[0.15241 + 16.722\,(x\theta/\pi)^{0.855} - 14.944\,(x\theta/\pi)]$ Eqn. 23

$F_b = 1.10 + x\,[-0.09967 + 5.0057\,(x\theta/\pi)^{0.565} - 2.8329\,(x\theta/\pi)]$ Eqn. 24

$x = a/t$ Eqn. 25

θ/π = ratio of crack length to pipe circumference

(SF) = Safety Factor

= 2.77 for normal operating/upset

= 1.39 for emergency/faulted

Note: K from transients are not considered per Code, [A.37].

7.4.2 For axial flaws, [A.37, H-7400, H-4221]:

$$K_I = K_{Im} + K_{Ir} \leq K_{Ic}$$ Eqn. 26

where:

$$K_{Im} = (SF)\frac{pR}{t}(\pi\alpha / Q)^{0.5} F \text{ ksi } \sqrt{\text{in}}$$ Eqn. 27

where

(SF) = Safety Factor

= 3.0 for normal operating (including upset and test) conditions

= 1.5 for emergency and faulted conditions

$$Q = 1 + 4.593\left(\frac{a}{l}\right)^{1.65}$$ Eqn. 28

$$F = 1.12 + 0.053\alpha + 0.0055\alpha^2 + (1.0 + 0.02\alpha + 0.0191\alpha^2)(20 - R/t)^2 / 1400$$ Eqn. 29

$$\alpha = (a / t)(a / l)$$ Eqn. 30

K_{Ir} = stress intensity factor due to residual stress with a safety factor of 1.0, ksi $\sqrt{\text{in}}$

$$K_{Ic} = (J_{Ic} E'/1000)^{0.5} \text{ ksi } \sqrt{\text{in}}$$ Eqn. 3

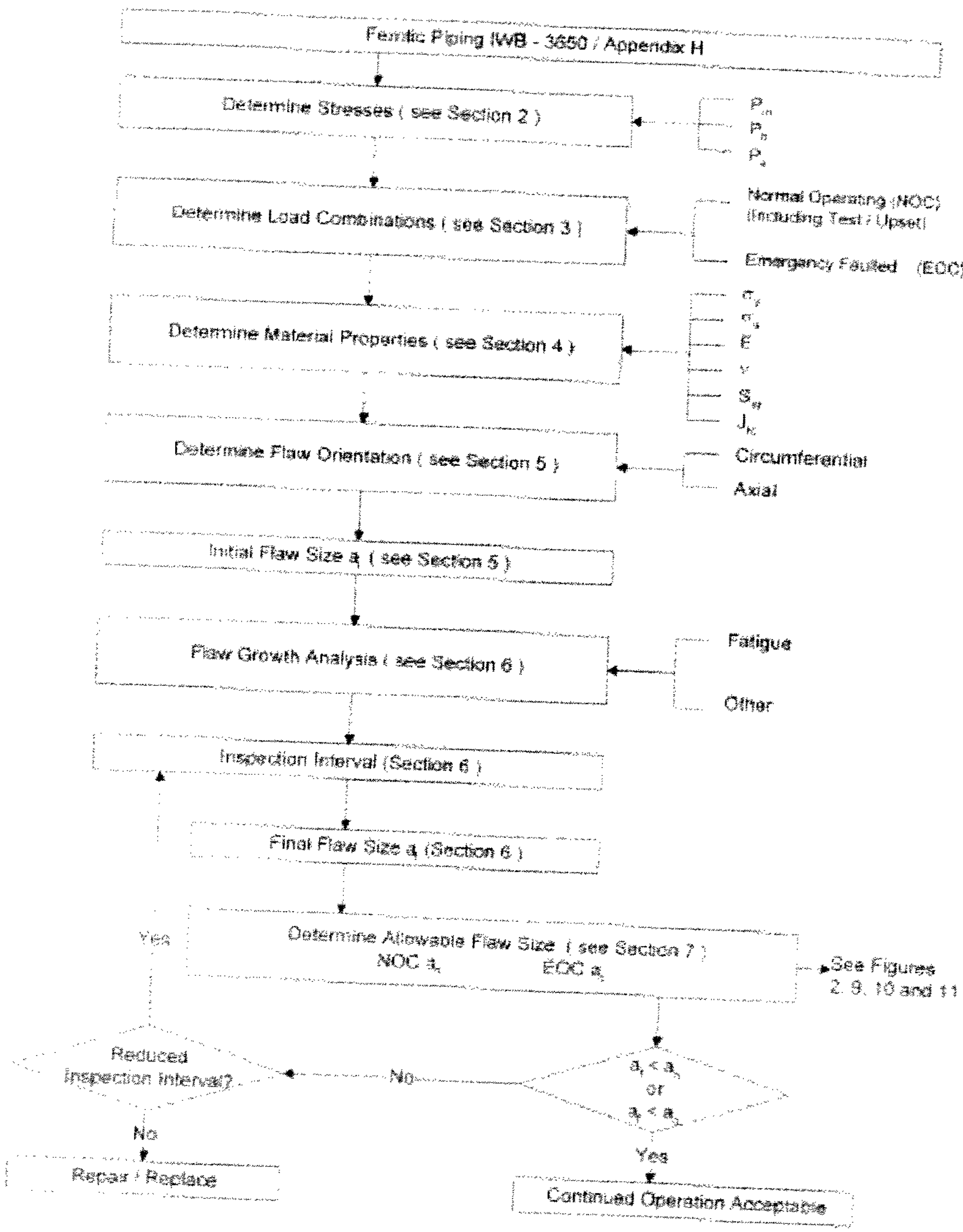


Figure 1: Flaw Evaluation Procedure for Ferritic Piping

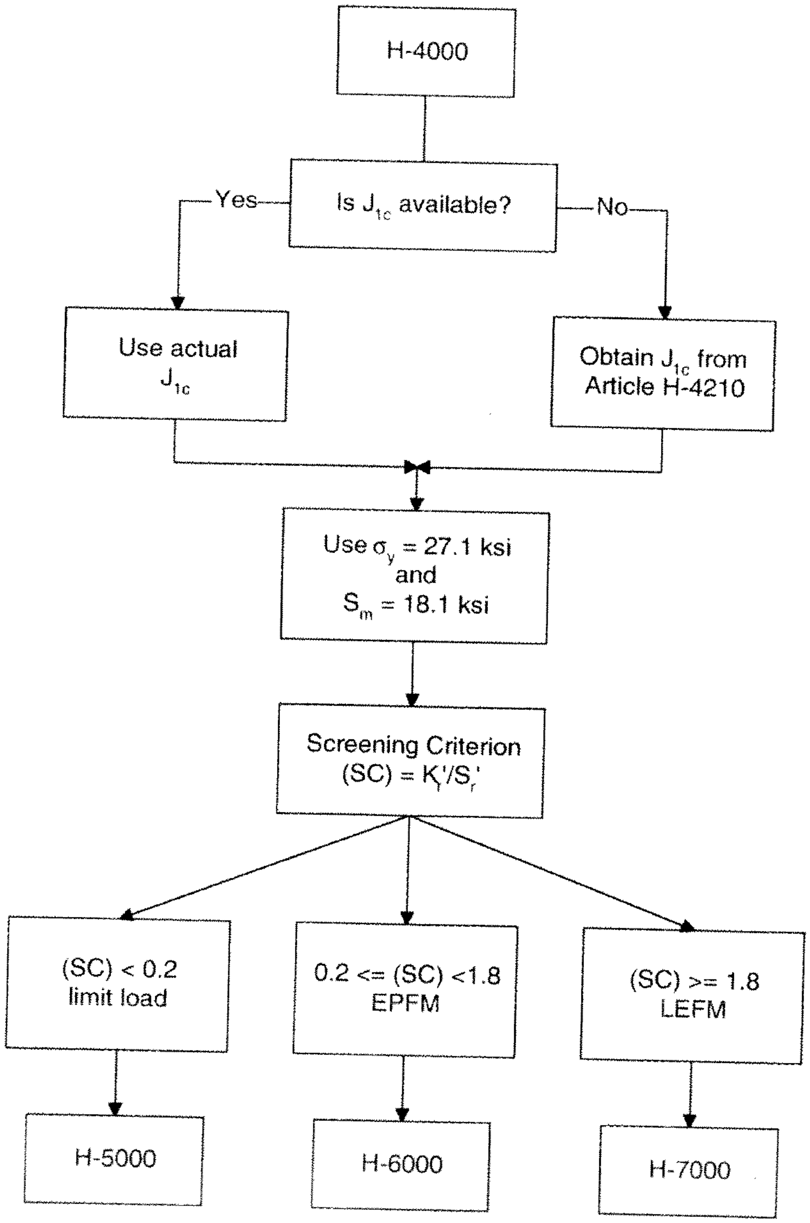
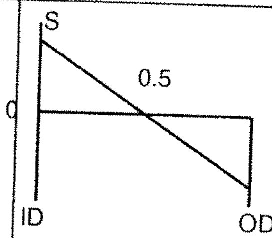
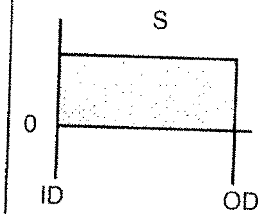
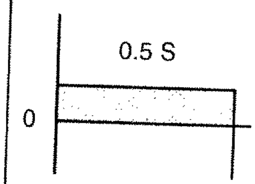


Figure 2: ASME Code Section XI Appendix H Flow Chart for Screening Criteria to Establish the Analysis Method [A.37]

Wall Thickness	Through-Wall Residual Stress [1]	
	Axial	Circumferential [2]
< 1 inch		
≥ 1 inch	See Note 3	

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

Figure 3: Recommended Axial and Circumferential Residual Stress Distributions for Circumferential Welds in Ferritic Pipe [A.13]

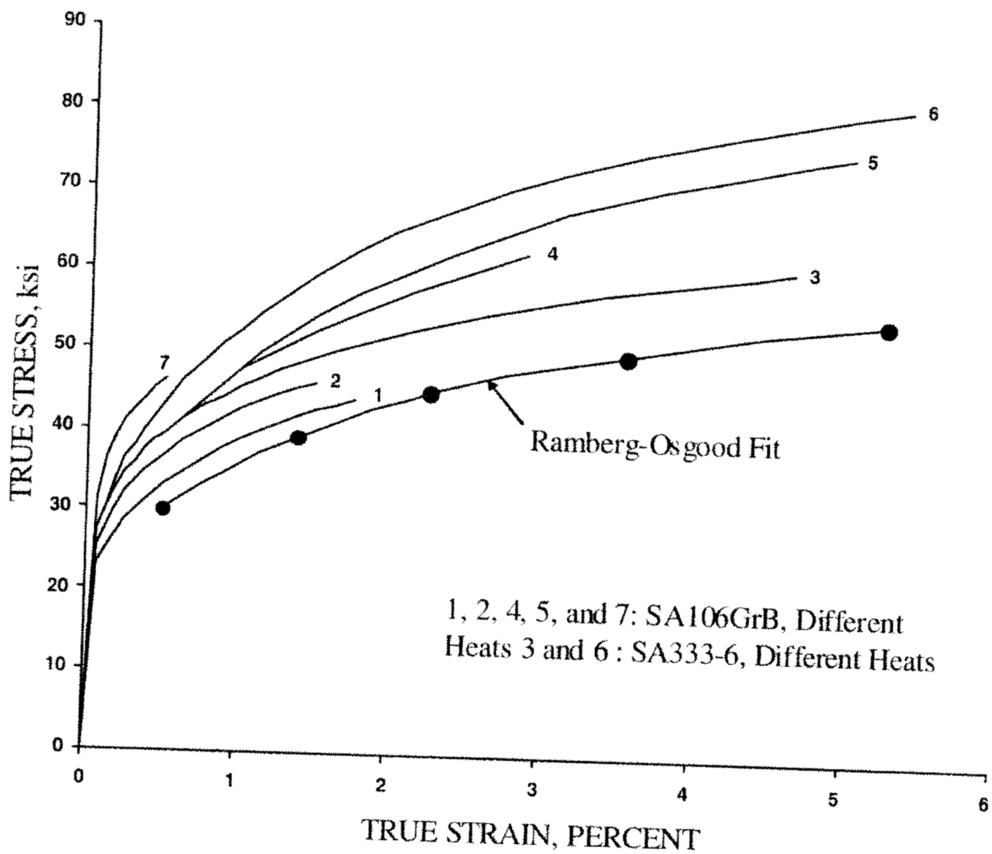


Figure 4: True Stress-Strain Curves for SA106 Gr. B and SA333 Gr. 6 at 550^0 F [A.13]

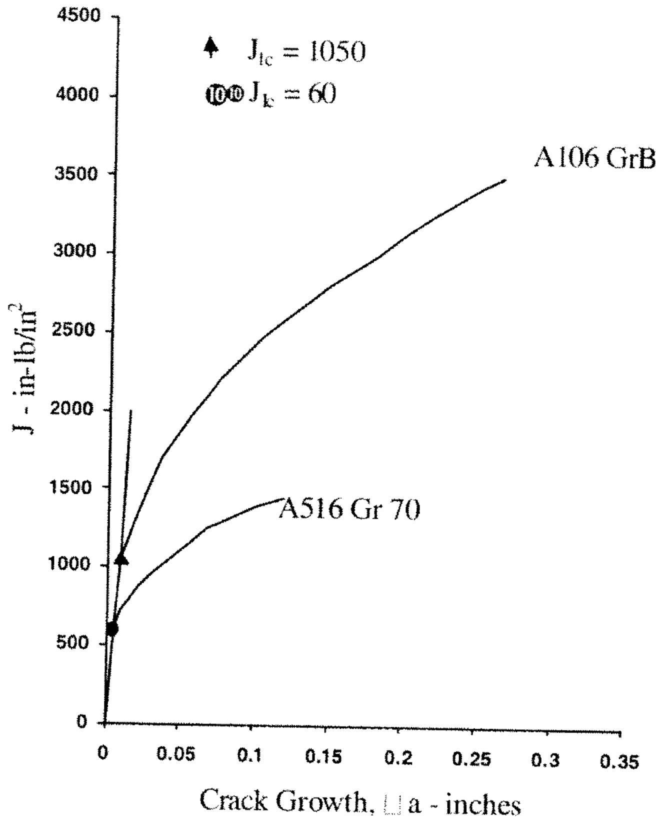


Figure 5: J-Resistance Behavior for A106 Gr. B (L-C Orientation) and A516 Gr. 70 (T-L Orientation) at 550^0 F [A.13]

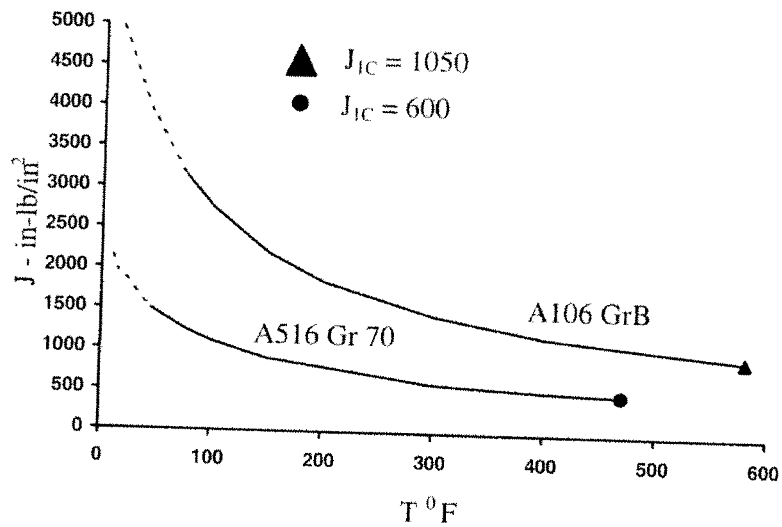


Figure 6: J / T Curves for Category 1 Materials [A.13]

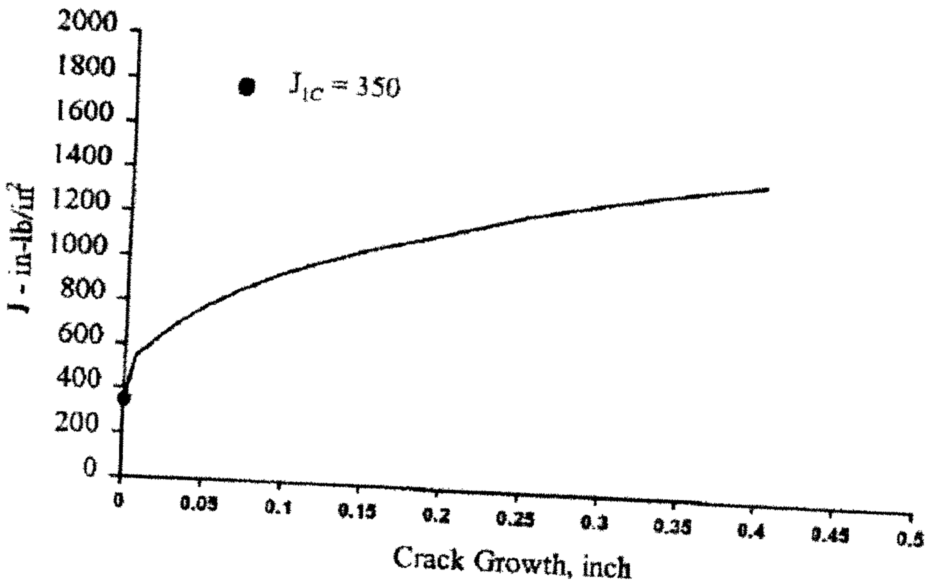


Figure 7: J-R Curve for Category 2 Materials [A.13]

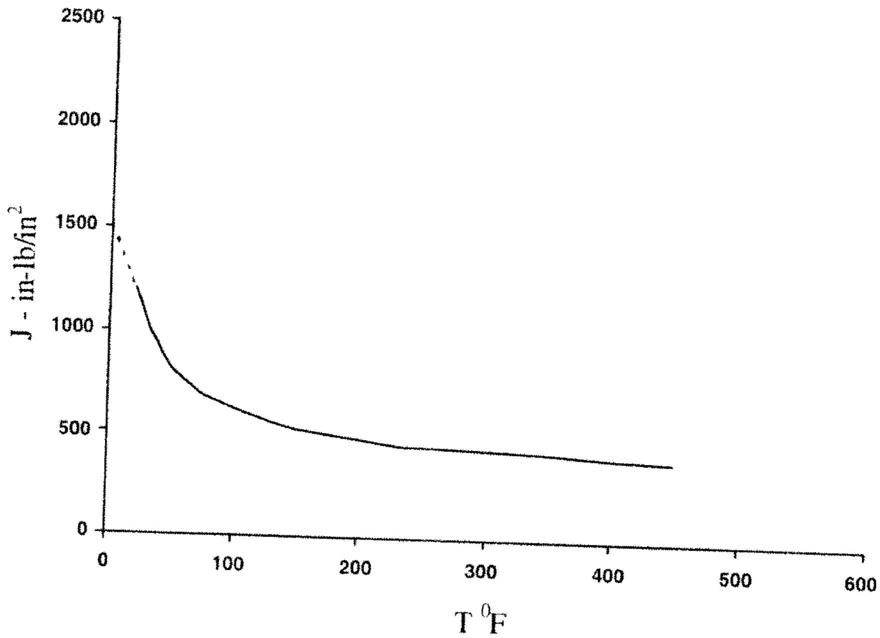


Figure 8: J/T Curve for Category 2 Materials [A.13]

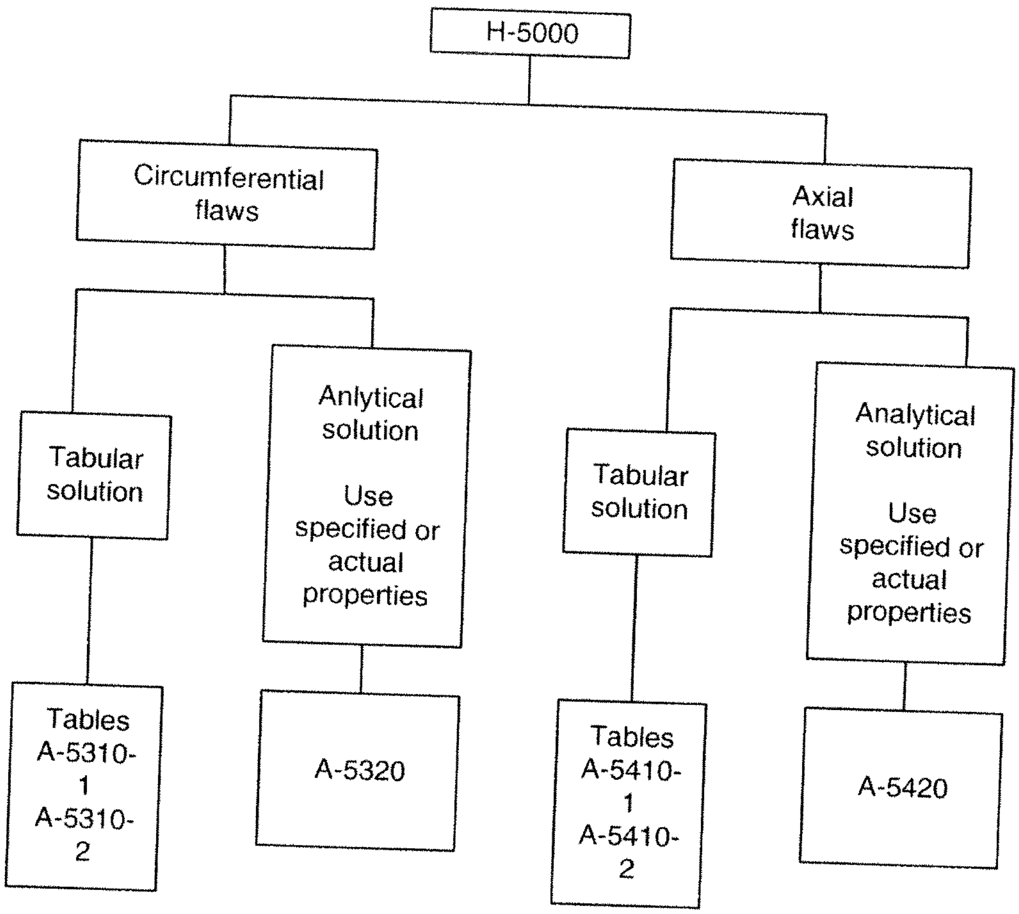


Figure 9: Flow Chart for Materials Meeting the Load Limit Criteria [A.37]

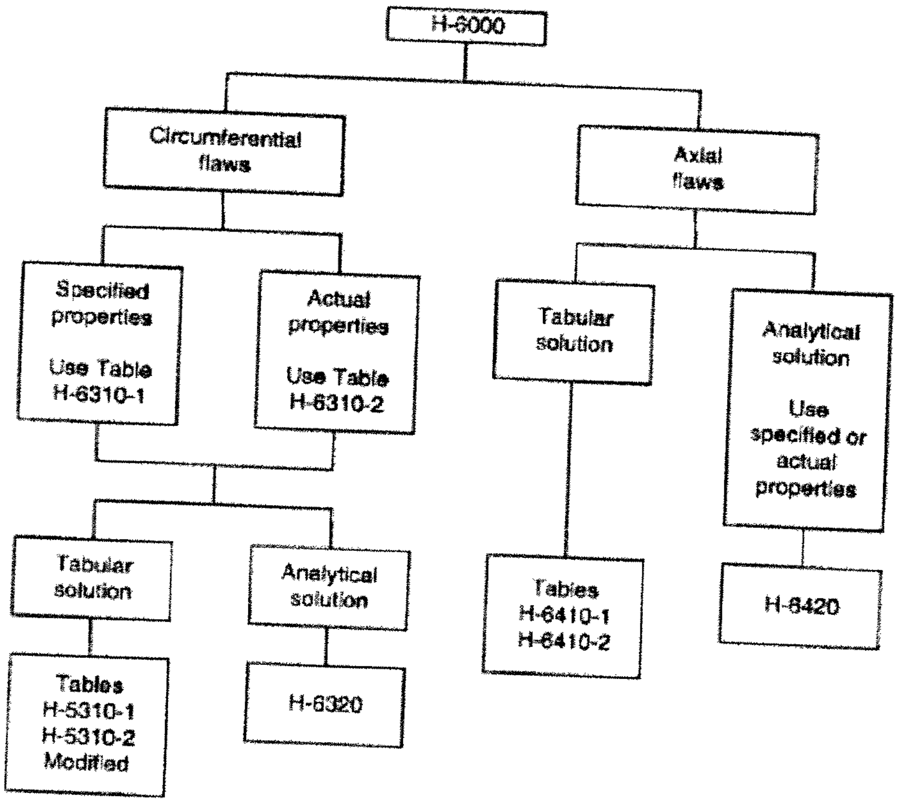


Figure 10: Flow Chart for Materials for which Ductile Flaw Extension May Occur Prior to Limit Load (EPFM) [A.37]

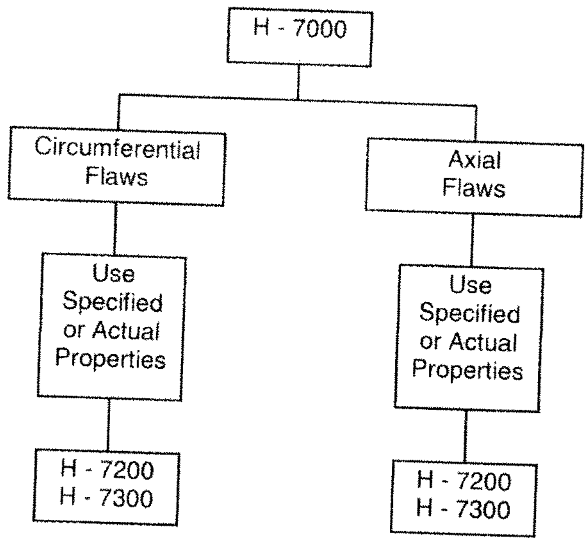
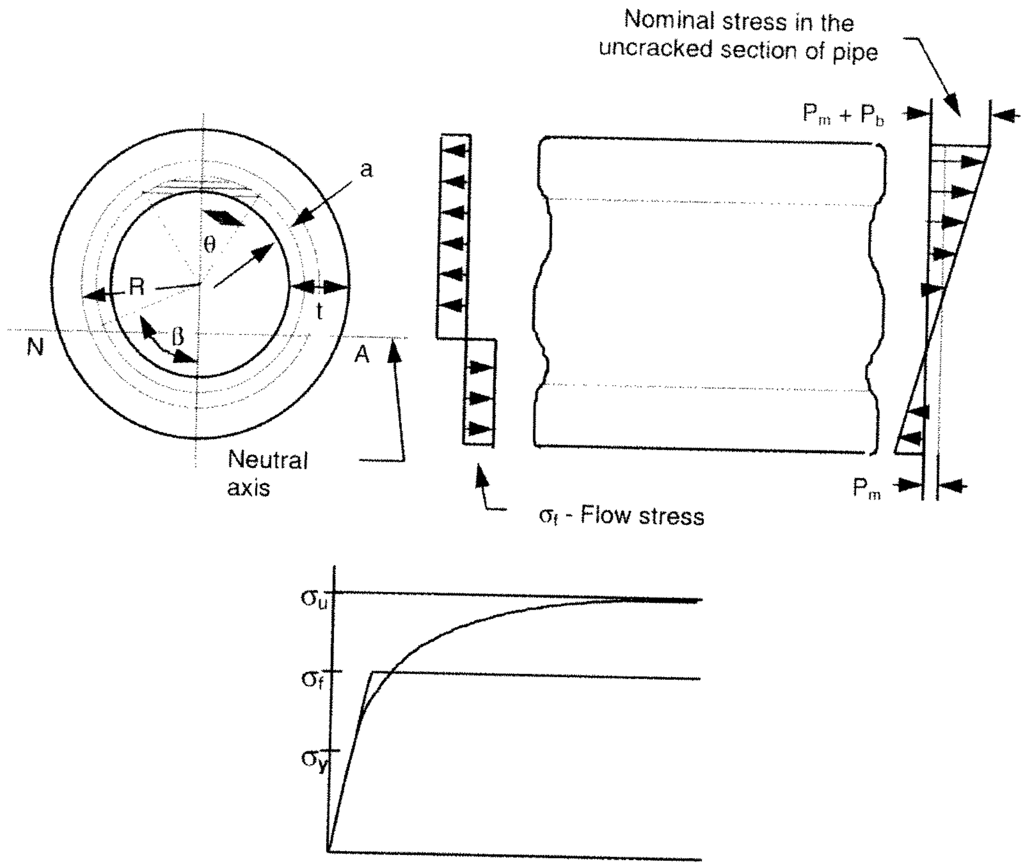


Figure 11: Flow Chart for Materials Meeting the Linear Elastic Fracture Mechanics (LEFM) Criteria [A.37]



Limit Load (Net section plastic collapse)

Figure 12: Stress Distribution in a Cracked Pipe -- Basis for Net Section Collapse Criteria for Austenitic Steel Pipe

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

Attachment XV: CLFE: Alternate Fracture Mechanics Solutions

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 K_I. Expressions have been developed in the literature for the calculation of the value of K_I 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:

$$K_I = C\sigma\sqrt{\pi a} \qquad \text{Eqn.1}$$

where:

σ = nominal applied stress

a = characteristic crack dimension such as crack depth for surface cracks

C = 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 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 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_I 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_{Ic} (the elastic-plastic fracture toughness) when available can be converted to K_{Ic} using the relationship

$$K_{Ic} = \sqrt{\frac{EJ_{Ic}}{\left(1-\nu^2\right)}}\ \text{ksi}\sqrt{\text{in}} \qquad \text{Eqn. 2}$$

where, J_{Ic} 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_I from the References A.23 through A.27. Safety factors shall be applied to the stresses to maintain Code safety margins. Compare K_I to K_{Ic} to ensure K_I 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_1.

3.1.3 For linear elastic cases,

$$J_1 = \frac{K_I^2}{E}(1-\upsilon^2) \qquad \text{Eqn.3}$$

3.1.4 Similar to the LEFM case, there is a parameter designated as J_{Ic} which measures the fracture toughness of the material. The values of K_{Ic} can be converted to J_{Ic} using the above expression. However, unlike the linear elastic case, unstable crack growth does not occur when the value of J_{Ic} is reached. Figure 1 shows the crack growth behavior of a typical ductile material. Upon reaching J_{Ic}, 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:

$$\frac{\varepsilon}{\varepsilon_o} = \frac{\sigma}{\sigma_o} + \alpha\left(\frac{\sigma}{\sigma_o}\right)^n \qquad \text{Eqn. 4}$$

where:

ε and σ = strain and stress, respectively

ε_0 and σ_0 = yield strain and yield stress, respectively

α and n = Ramberg-Osgood material coefficients

3.2.2 Values of α 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]:

$$J = J_e + J_p \qquad \text{Eqn. 5}$$

where:

J_e = the elastic contribution

J_p = the plastic contribution

3.2.4 The expressions for J_e and J_p 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° 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_{Ic}. It should be emphasized though that the Code safety factors should be applied to the piping loads to maintain Code margins. Values of J_{Ic} 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_{Ic}, 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:

$$J_{Applied} = J_{Material} \Rightarrow \text{(No Crack Propagation)} \qquad \text{Eqn. 8}$$

3.3.3 For Stability:

$$J_{Applied} > J_{Material} \Rightarrow \text{Crack Propagation} \qquad \text{Eqn. 9}$$

$$\frac{dJ_{Applied}}{da} \leq \frac{dJ_{Material}}{da} \Rightarrow \text{Stability} \qquad \text{Eqn. 10}$$

$$\frac{dJ_{Applied}}{da} > \frac{dJ_{Material}}{da} \Rightarrow \text{Instability} \qquad \text{Eqn. 11}$$

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

$$T = \frac{dJ}{da}\frac{E}{\sigma_o^2} \qquad \text{Eqn. 12}$$

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 Δa 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 360^0 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

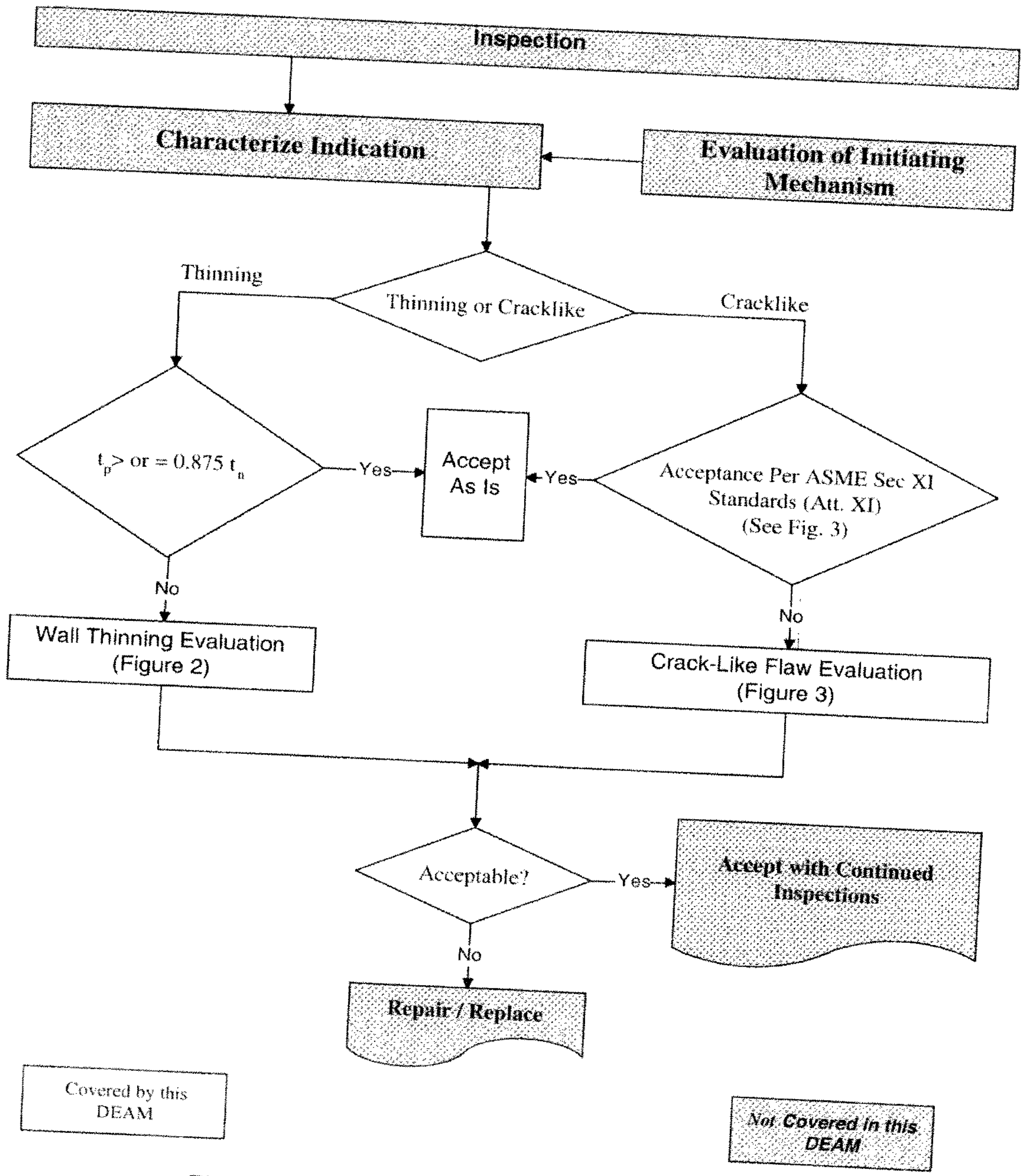
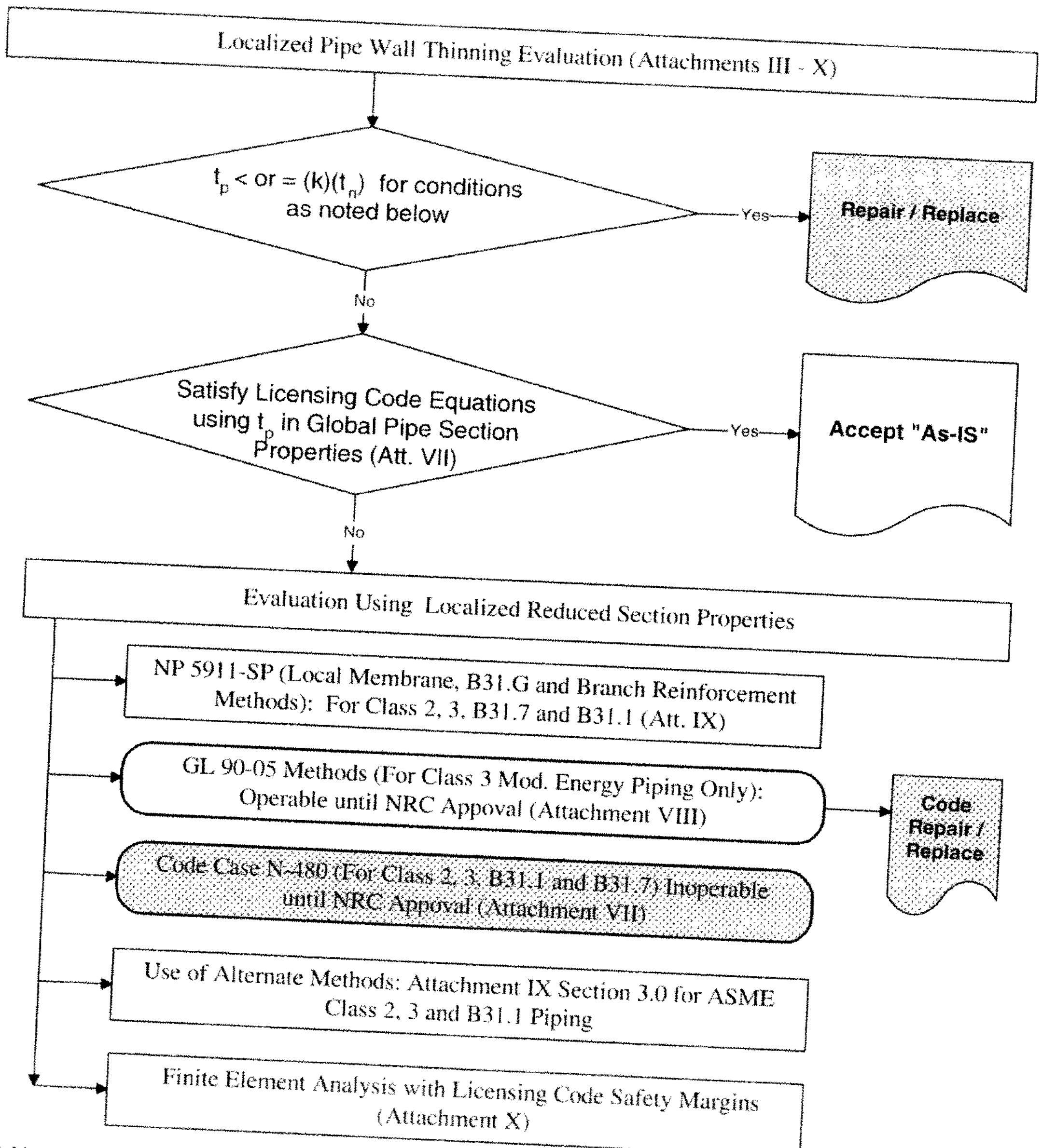


Figure 1: Overall Flow Chart For Evaluations

Attachment 7.9: Informational Attachment



* 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
kt_n = lesser of $0.3t_n$ and $0.5\ t_m$ 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

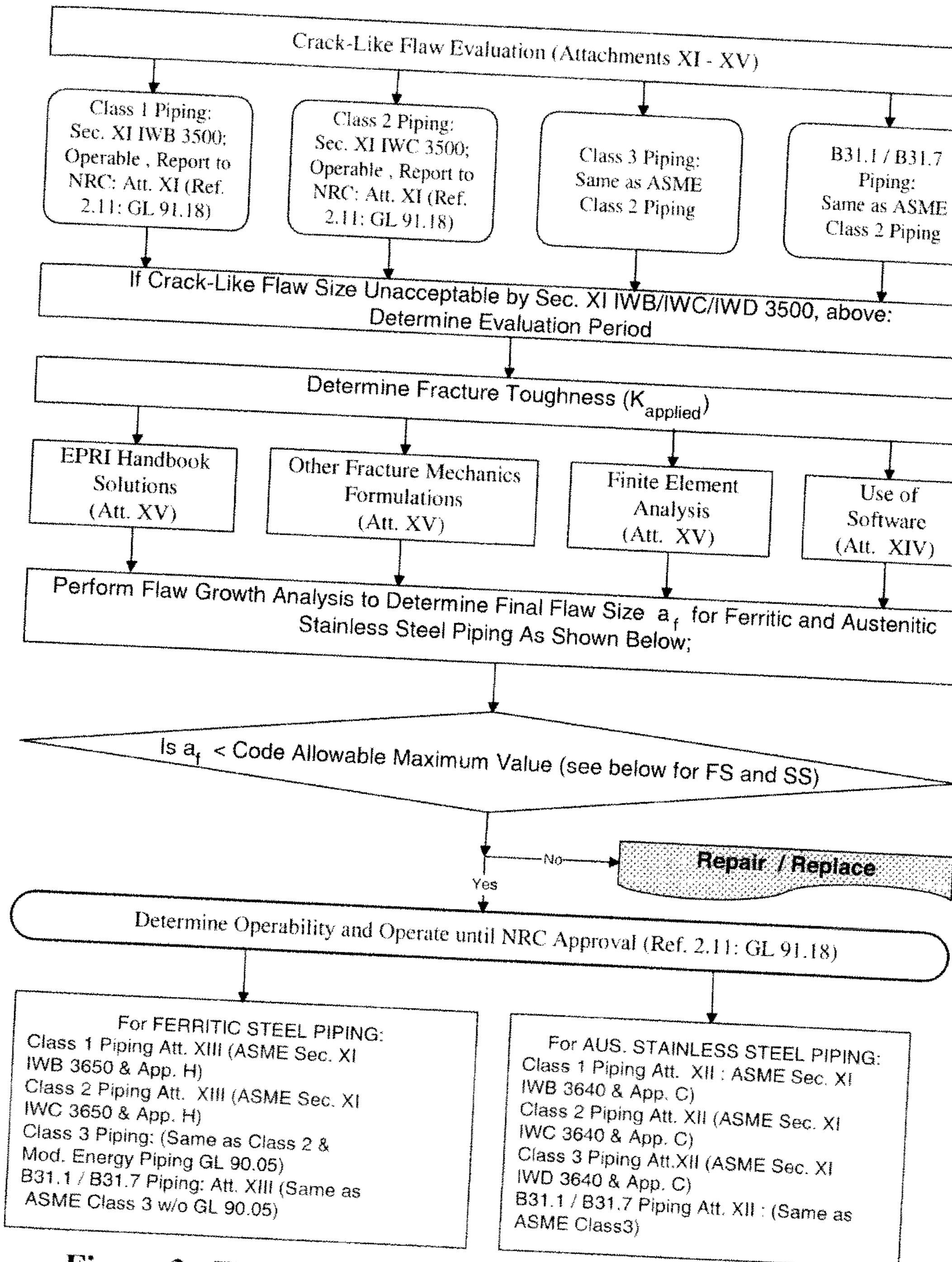


Figure 3: Flow Chart for Evaluation of Crack-like Flaws