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ABSTRACT

As part of the structural integrity assessment for Savannah River Site (SRS) piping systems, an acceptance criteria methodology for minimum pipe wall thickness has been developed for carbon steel piping. If a measured pipe thickness during inspection cannot meet the 87.5% of the nominal wall thickness specified in the ASME Code Case N-480, the acceptance criteria must be invoked.

For a particular pipe, the larger of the two minimum thickness values obtained from the code stress check and the CEGB-R6 Failure Assessment Diagram (FAD) methodology is the minimum wall thickness for the acceptance criteria. The code stress check is based on the ASME/ANSI B31.1 Code, ASME Code Case N-480, and the SRS reactor restart criteria. The pipe wall thickness is calculated from the code equations and the applied loads. In fracture analysis, three types of axial and circumferential flaws are assumed to exist in the pipes based on the weld defects found in service history. For each flaw configuration, the stress intensity factors and the limit load solutions are calculated. These quantities are input to FAD to solve for the corresponding wall thickness required for the pipe to sustain the postulated flaws and to meet ASME safety margins under the applied loads.

INTRODUCTION

The structural integrity and safety margins are maintained for the piping systems by providing acceptance criteria for wall thinning. The technical bases for calculating minimum thickness requirements have been developed at Savannah River Technology Center (SRTC) [1,2,3,4] and are summarized here with some modifications. The minimum requirements for the wall thickness will satisfy the code stress criteria and fracture criteria. The American Society of Mechanical Engineers (ASME) code-based factors of safety on loading defined in Reference 5 for acceptance-by-analysis are used for thinned pipes containing postulated design flaws.

Carbon steel pipes (A53 Grade A, A53 Grade B, and A285 Grade B) in an emergency pump room are used for demonstrating the calculations. The pipe sizes include 4, 6, 12, 14, 18, 24, 30, and 36-inch nominal diameters. The results of piping stress analyses carried out earlier were used for input to wall thinning calculations. Minimum wall thickness requirements were calculated based on: 1) SEP-7 [6] or SEP-24 [7]; 2) B31.1 [8] or ASME Code Case N-480 [9]; and 3) CEGB-R6 Failure Assessment Diagram (FAD) [10]. The most conservative thickness is used for the wall thinning acceptance criteria.

The ASME code stress intensification factors were applied at pipe bends and branch connections. The pipe wall is assumed to contain a pre-existing flaw, or "design flaw." Both the linear elastic fracture mechanics solution for stress intensity factors and the limit load solution were obtained to form a data point on the FAD. If this point is inside of the material curve, then the configuration (wall thickness, flaw size, and orientation) is acceptable (Figure 1). An iterative numerical procedure was developed [1,2,3] to solve for the wall thickness corresponding to the design flaws and the applied load so that this data point is exactly on the FAD material curve.

The larger of the two minimum thickness values obtained from the code stress check and the FAD methodology for a particular pipe is the minimum wall thickness for the acceptance criteria. The acceptable flaw sizes for the piping under loads were calculated to ensure that none of the postulated (or design) flaw sizes exceed the ASME code-based acceptable flaw sizes. The current acceptance criteria will provide first screening/disposition of the pipe thickness inspection results when the pipe wall loss is found to be greater than 12.5% of its nominal (design) thickness [9]. Any measured thickness exceeding the acceptance criteria will require repair/replacement of the pipe segment, or a customized analysis (and/or localized thinning analysis) considering detailed stress distribution of the pipe should be carried out.

MATERIALS OF CONSTRUCTION

Tensile Properties

The piping material properties used in this analysis are listed in Table 1:

TABLE 1 Piping Material Properties

Material	Yield Stress† (ksi)	Ultimate Stress† (ksi)	Allowable Stress†† (ksi)
A53 Gr. A	30	48	12
A53 Gr. B	35	60	15
A285 Gr. B	27	50	12.5
Young's Modulus = 29,500 ksi			

(†) Values of yield stress and ultimate stress were obtained from Reference 1.

(††) Allowable stress values (denoted by S_h in Equations 1 to 2 and by SE in Equation 5) are the product of the design stress at 200°F from the ASME B31.1 Code [8] and the weld joint efficiency.

In the current analysis, wall thicknesses are based on the values used in the piping stress analyses which are in turn based on actual walkdown of the piping. The material of construction and the nominal wall thickness for each line can be found in Table 2.

Fracture Toughness

The static and dynamic fracture toughness tests were performed with compact tension specimens prepared from SRS L-Reactor archival carbon steel piping at the minimum operating temperature of 40°F [11]. The A285 material had the highest average value of static fracture toughness (K_{IC}) of 205 ksi$\sqrt{in}$ (based on four specimens). This value is about 50 ksi$\sqrt{in}$ higher than that for the static toughness of the welds and the American Society for Testing and Materials (ASTM) A53 material. The lowest static fracture toughness of 138 ksi$\sqrt{in}$ occurred in ASTM A53, P4 plate material. In the present development, a fracture toughness value of 80 ksi$\sqrt{in}$ is adopted for both A285 and A53 materials.

WALL THINNING ANALYSIS

Overview

The minimum wall thicknesses are estimated from two major approaches. In the first approach, the wall thickness is obtained from the equations defining acceptable code stress [6,7,8] with a given set of applied loads based on existing results of piping stress analysis. The code-based stress intensification factors due to pipe bends and branch connections are also applied.

The second approach utilizes the FAD involving the applied loads, postulated flaw configurations [1], linear elastic fracture mechanics solutions, plastic limit load solutions or ligament yielding criterion, and a material failure curve. In the present analysis, the material failure curve was obtained based on the measured tensile properties of A285 carbon steel [1,11]. By continuously removing pipe wall material to simulate thinning of the pipe, the applied load curve will approach the material curve. The required minimum wall thickness is determined at the intersection point of these two curves (Figure 1). At this wall thickness, the pipe is still capable of sustaining the postulated flaws for the given applied loads. Of course, the postulated flaws are also subjected to shape changes due to the postulated pipe wall loss. As an example, a circumferential semi-elliptic or thumbnail flaw may become shallower in depth and shorter in length if the wall loss has occurred on the cracked surface of the pipe.

Acceptable minimum wall thickness shall be greater than 30% of the nominal thickness (t_o), as required in ASME Code Case N-480 [9]. Therefore, any code stress based thickness (calculated with the above equations) less than $0.3t_o$ will be reset to $0.3t_o$.

Code Stress Check

Allowable Thickness Based on Mechanical Loading. Wall thinning due to erosion, corrosion, or crack-like flaws affect the maximum stress in the piping. However, the governing equations in the code are based on simple pipe geometry and do not take into account local wall thinning. A conservative methodology assuming uniform thinning all around the pipe section is used here in the analysis. Wall thinning affects the code equations through three parameters: 1) the section modulus is reduced, 2) the stress intensification factor (SIF) is increased, and 3) the ratio D_o/t is increased. The effect of the ratio D_o/t is not addressed in the B31.1 Code [8], and therefore, the guidance is taken from SEP-24 [7] to modify the code equations [1]. The governing equations are as follows:

(1) Normal Operating Conditions (based on Reference 6)

$$\text{For } \frac{D_o}{t} \le 50 \qquad \frac{PD_o}{4t} + \frac{0.75i}{Z}(M_a) \le S_h \tag{1}$$

$$\text{For } \frac{D_o}{t} > 50 \qquad \frac{PD_o}{4t} + \frac{0.75i\,(M_a)}{(1.3-0.006\frac{D_o}{t})Z} \le S_h \tag{2}$$

(2) Occasional Loading Conditions (based on Reference 7)

$$\text{For } \frac{D_o}{t} \le 50 \qquad \frac{PD_o}{4t} + \frac{0.75i}{Z}(M_a + M_b) \le 2\,S_y \tag{3}$$

$$\text{For } \frac{D_o}{t} > 50 \qquad \frac{PD_o}{4t} + \frac{0.75i\,(M_a + M_b)}{(1.3-0.006\frac{D_o}{t})Z} \le 1.5\,S_y \tag{4}$$

Where

- P is the internal design pressure, psig.
- D_o is the outside diameter, in.
- D_i is the inside diameter, in.
- t is the wall thickness at a thinned cross section, in.
- i is the SIF and is a function of t, $0.75i \geq 1.0$.
- Z is the section modulus of the thinned pipe, $Z = \frac{\pi(D_o^4 - D_i^4)}{32D_o}$, in^3.
- M_a is the resultant bending moment due to sustained loading, in-lb.
- M_b is the resultant bending moment due to occasional loading, in-lb.
- S_h is the material allowable stress in Table 1.
- S_y is the yield stress in Table 1.

Allowable Thickness Based on Thermal Loading. This piping system was operated at close to atmospheric temperatures and, therefore, the thermal stresses are negligible.

Allowable Thickness Based on Internal Pressure. Pressure design of the piping requires that minimum wall thickness be calculated using the following code equation [8]:

$$t_m = \frac{PD_o}{2(SE + Py)} \qquad (5)$$

Where SE is the material allowable stress from the ASME B31.1 Code [8] and it includes the piping weld joint efficiency. The SE values are given in Table 1. The material allowable stresses used in the wall thinning analysis are based on the materials identified (Table 2) in previous piping stress analyses; and y is the coefficient given in Table 104.1.2(A) of the B31.1 Code. The value of this coefficient is 0.4 for the piping system

Fracture Analysis

The fracture analysis provides the basis for FAD methodology in developing wall thinning criteria. In the service history of SRS, no service-induced flaws have ever been reported in this piping system. However, flaws must be assumed to exist for this life extension analysis. The minimum wall thickness required to sustain the design flaws in an already thinned pipe wall is estimated by FAD methodology according to the normal and off-normal operating conditions. Three types of design flaws were adopted: 1) a part-throughwall circumferential flaw 5-inch long and 60% deep; 2) a throughwall axial flaw with length twice of original pipe wall thickness; and 3) a long, 25% part-throughwall axial flaw.

Most materials behave with elastic-plastic response. In general, the solutions for elastic-plastic fracture parameters (such as J-integral) may not be available. The FAD is used to bridge the regimes of linear elastic solution and plastic or limit load solution. Its concept is also used by ASME code [5] for a screening criterion to determine the appropriate deformation mode. In the FAD-based wall thickness calculations, both linear elastic solution for stress intensity factors and plastic solution for limit loads are evaluated.

To provide general wall thinning acceptance criteria, only the maximum operating pressure (70 psi), M_a (bending moment resultant at normal operation), and M_b (bending moment resultant at off-normal operation) are used. The axial forces due to pipe supports are negligible compared to the forces due to internal pressure and the bending moments.

ASME code-based factors of safety for evaluating ferritic piping flaws are used with the applied loads in the fracture analysis [1,5]. The factors of safety of 2.77 and 1.39 are applied in the cases of circumferential flaws under normal and off-normal (emergency/faulted) operating conditions, respectively. For axial flaws, values of 3 and 1.5 are applied, respectively, under the normal and off-normal operating conditions. These values are universally defined in ASME Section XI, Appendix H [5] for analysis methods with linear elastic fracture mechanics, elastic-plastic fracture mechanics, or limit load.

Failure Assessment Diagram (FAD) Methodology Based on the actual measured tensile properties, the material failure curve in FAD can be constructed by

$$K_r = \left(\frac{E}{L_r} \frac{\varepsilon_{ref}}{\sigma_y} + \frac{L_r^3}{2E} \frac{\sigma_y}{\varepsilon_{ref}} \right)^{-1/2} \quad \text{for} \quad L_r \le L_r^{max} \text{ and}$$

$$K_r = 0 \quad \text{for} \quad L_r > L_r^{max}$$

where L_r and K_r are respectively the abscissa and ordinate of the CEGB-R6 FAD (Figure 1) [10], E is the Young's modulus of the material, σ_y is the 0.2% yield stress, and $L_r^{max} = \sigma_f/\sigma_y$ is the limit load cut-off (σ_f is the flow stress defined by the average of yield stress and ultimate stress). The quantity ε_{ref} is a reference strain corresponding to a reference stress level of $\sigma_{ref} = L_r\sigma_y$ in the true stress-true strain curve of the material. It has been determined in Reference 1 that A285 curve is more limiting; therefore, it is used as the material failure curve for both A285 and A53 carbon steels throughout the FAD analysis. Tabulated data of L_r and K_r for constructing A285 and A53 failure assessment diagrams can be found in Reference 1.

The generic definitions for K_r and L_r due to applied loads are [10]:

$$K_r = \frac{K_I}{K_{mat}} \text{ and } L_r = \frac{\text{Applied load that contributes to the plastic collapse}}{\text{Plastic yield load of the flawed structure}},$$

where K_I is the stress intensity factor due to the applied load including the residual stress contribution and K_{mat} is a fracture toughness value relevant to the analysis (in the present case, $K_{mat} = K_{IC}$). The specific expressions for K_r and L_r are reported in the latter part of the paper for each crack configuration.

A pair of L_r and K_r can be calculated as a function of applied load, wall thickness, and a flaw configuration. As shown in Figure 1, if a point on FAD corresponding to a pair of (L_r, K_r) is inside the region bounded by the material failure curve, $L_r = 0$ (vertical axis), and $K_r = 0$ (horizontal axis), then the flaw is stable or acceptable for the given conditions. If this point falls outside the acceptable region, flaw growth is expected and pipe operating under such conditions is unsafe. In the present calculations for FAD-based wall thinning acceptance criteria, the applied load and the flaw configuration are fixed. By continuously reducing the wall thickness, the FAD applied load curve eventually intersects the material failure curve (Figure 1). At this moment the wall thickness corresponding to the intersection point defines the minimum pipe wall thickness based on FAD.

Flaw Postulates. Among the majority (99%) of defect sizes found in SRS weld qualifying programs, a 5-inch long, 60% throughwall defect was identified for a circumferential flaw postulate [1] which would lead to a conservative fracture assessment. For axial flaws, the weld defect data are not applicable. Reference 1 proposed two flaw postulates in the pipe axial direction based on ASME Section XI [13]. These axial flaws are 1) a long 25% part-throughwall and 2) a throughwall flaw with length twice of its design thickness. The postulated defects were treated as ideal cracks in the fracture mechanics assessment.

These three types of flaws are separately evaluated with the FAD methodology to determine the minimum requirements for the wall thickness. The most conservative estimate among these three resulting thicknesses is the minimum thickness (based on FAD) for that segment of pipe.

Part-Throughwall Circumferential Cracks.

(1) Stress Intensity Factor - Solution for K_r

An elliptic crack is assumed to exist in the inside surface of the pipe with thickness t, inside radius R_i, and outside radius R_o. The mean radius is denoted by R. The crack length along the inside surface of the pipe is 2c (at an angle 2θ) and the deepest penetration is the depth a (Figure 2). The stress intensity factor (K_I) under axial tension is [14]

$$K_I = \sigma F \sqrt{\pi t}$$

where

$\sigma = \sigma_m + \sigma_b$ is the maximum tensile stress,

σ_m is the membrane (longitudinal) stress in the pipe,

$\sigma_b = \frac{M}{Z} = \frac{M}{\pi (R_o^4 - R_i^4)/(4R_o)}$ is the maximum bending stress in the outer surface of the pipe,

$M = M_a$ is the bending moment at normal operating condition,

$M = M_a + M_b$ is the bending moment at off-normal operating condition, Z is the elastic section modulus, and F is a geometric function.

Defining $\beta = \frac{a/t}{(0.25+a/c)^{0.58}}$, the values of function F are

$$F = 3.702\beta - 13.475\beta^2 + 20.0\beta^3 + 0.0086\beta(R/t-5) \quad \text{for } \beta<0.25 \text{ and } 5\leq R/t\leq 20,$$

$$F = 3.831\beta - 13.475\beta^2 + 20.0\beta^3 + 0.002\beta(R/t-20)^{0.7} \quad \text{for } \beta<0.25 \text{ and } 20\leq R/t\leq 160,$$

$$F = 0.25 + 0.4868\beta + 0.3835\beta^2 + 0.0086\beta(R/t-5) \quad \text{for } \beta\geq 0.25 \text{ and } 5\leq R/t\leq 20, \text{ and}$$

$$F = 0.25 + 0.6158\beta + 0.3835\beta^2 + 0.002\beta(R/t-20)^{0.7} \quad \text{for } \beta\geq 0.25 \text{ and } 20\leq R/t\leq 160.$$

The conditions of applicability are

$0.05\leq a/t\leq 0.8$, $2c/a\geq 3$, $\theta\leq\pi$, and $5\leq R/t\leq 160$.

As the pipe wall thins, the flaw geometry may also change. Figure 3 shows a semi-elliptic flaw on a flat plate. When the amount of wall loss on the cracked side is h, the post-wall loss flaw length becomes $2c \cos\left(\sin^{-1}\frac{h}{a}\right)$. For a part-throughwall elliptic crack in the circumferential direction of a cylindrical shell or a pipe, the post-wall loss length is approximated by that flat plate formula. The post-wall loss depth of the flaw at the deepest penetration is, of course, a-h.

The stress intensity factor due to applied loads is calculated above. Together with the stress intensity factor due to residual stress, the parameter K_r on FAD can be obtained.

(2) Uncracked Ligament Yielding - Solution for L_r

Carbon steels do not exhibit high ductility at temperatures near the transition from ductile to cleavage fracture. Therefore, the limit load solutions based on entire cross section yielding, normally used with the austenitic steel piping, are not appropriate for carbon steels. An elastic solution is obtained for the uncracked ligament such that the maximum Mises stress ($\bar{\sigma}$) at the outer fiber of the pipe is not to exceed the yield stress (σ_y) in tension [1], that is

$$\bar{\sigma} = \sqrt{\sigma_L^2 + \sigma_h^2 - \sigma_L\sigma_h + 3\tau^2} \leq \sigma_y \text{ ,}$$

where σ_L is the longitudinal stress, $\sigma_L = \frac{F_a}{A_c} + \frac{M - F_a\bar{y}}{Z_c}$,

σ_h is the hoop stress ($\sigma_h = \frac{PR}{t}$) due to internal pressure P, and

τ is the torsional stress which in the present analysis is not considered and is set to zero.

In the above expressions, F_a is the total force acting along the pipe longitudinal axis. This force may include the longitudinal force $\left(P\pi R_i^2\right)$ due to the internal pressure and contributions from other sources (not considered in this analysis). Note that the second term in the equation for σ_L represents the bending stress. The total moment is increased from the magnitude of applied moment (M) to ($M - F_a\bar{y}$) due to a shift of neutral axis ($\bar{y}$ is the location of the neutral axis in the Y-direction and is negative in the coordinate system shown in Figure 4) when a crack is present.

For simplicity, the crack is assumed to have the configuration of Figure 4 with straight edges instead of an elliptic contour. The crack angle is 2θ and the crack depth (d) is uniform through the current pipe wall thickness t. It can be shown that the cracked sectional area (A_c), the location of the neutral axis in the Y (vertical) direction ($\bar{y}$), and the elastic section modulus (Z_c) are:

$$A_c = 2\pi Rt\left[1 - \frac{\theta d}{\pi t} + \frac{\theta d(t-d)}{2\pi Rt}\right] ,$$

$\bar{y} = -\frac{2d\sin\theta}{A_c}\left(R_i^2 + R_i d + \frac{1}{3}d^2\right)$ (pure bending and linear elastic stress state are assumed),

[The negative value indicates that the neutral axis is below the center (centroid) of the uncracked cross section.]

$$Z_{c,top} = \frac{I_{NA}}{R_o - \bar{y}} \text{ and } Z_{c,bot} = -\frac{I_{NA}}{R_o + \bar{y}} ,$$

where $Z_{c,top}$ and $Z_{c,bot}$ are the elastic section moduli for calculating bending stresses at the top (crack side) and the bottom (compression side), respectively,

$I_{NA} = I_o - \bar{y}^2 A_c$ is the moment of inertia about the neutral axis,

$I_o = \frac{1}{8}\{[R_o^4 - (R_i + d)^4](2\theta + \sin 2\theta) + [R_o^4 - R_i^4](2\pi - 2\theta - \sin 2\theta)\}$ is the moment of inertia about the horizontal (X) axis of the pipe cross section,

Note that R_o, R_i and R correspond to the <u>current</u> pipe size (post-thinning configuration).

The FAD parameter L_r is then defined for this case as

$$L_r = \frac{FS\ \bar{\sigma}_{max}}{\sigma_y'},$$

where $\bar{\sigma}_{max}$ is the maximum Mises stress in the cracked cross section, either located on the top or on the bottom of the cross section; FS is the factor of safety; and σ_y' is a reduced yield stress which is approximated by:

$\sigma_y' = \sigma_y \frac{M_u}{M_p} \frac{4}{\pi}$ and σ_y' shall not exceed σ_y, the yield stress of the material [1].

The factor $\frac{M_u}{M_p}$ is the ratio of ultimate buckling moment (M_u) to the fully plastic moment (M_p) and is given in References 1 and 15:

$\frac{M_u}{M_p} = 1$ when $\alpha = \frac{E}{\sigma_y}\frac{t}{D_o} \geq 14$ (Fully plastic collapse),

$\frac{M_u}{M_p} = 0.775 + 0.016\alpha$ when $\alpha < 14$ (Inelastic Buckling), or

$$\frac{M_{u,elastic}}{M_p} = \frac{\frac{2(0.165)Et}{D_o} Z_{el}}{\sigma_f Z_{pl}} = \frac{\pi}{4}\frac{0.33Et}{D_o \sigma_f}$$, when the elastic buckling occurs ($\alpha << 14$),

where

$Z_{el} \cong \pi R^2 t$ is the elastic section modulus for an uncracked pipe,

$Z_{pl} = 4R^2 t$ is the fully plastic section modulus, and D_o is the outside diameter of the pipe.

<u>Residual Stress Intensity Factors</u>. When the welding process is completed and the weld returns to the ambient temperature from its molten state, residual stresses are developed perpendicular and parallel to the weld due to contraction. More deformation occurs along the weld direction because of longer length for cooling. A circumferential weld contracts to reduce the diameter leading to the development of bending type residual stress across the thickness. This residual stress distribution is perpendicular to the weld and tends to open a circumferential flaw or defect if it exists. On the other hand, the axial contraction of an axial weld will be limited by the axial stiffness of the pipe. A tensile residual stress is developed along the axial weld when it contracts. This residual stress is

parallel to the weld or axial weld defects/flaws, if any. Therefore, in this analysis the residual stress is considered only in the calculations of stress intensity factor for a circumferential flaw [1]. Residual stress will not be addressed for limit load-type analysis, because the residual stress are relieved after extensive yielding and crack growth have occurred.

Two types of residual stress distributions are used throughout the development of wall thinning criteria for the secondary and service reactor piping systems. When the pipe diameters are 12 inches and above, a tension-compression-tension type stress pattern is assumed (Figure 5). For smaller pipes, a bending type stress distribution is employed (Figure 6).

(1) Stress Intensity Factor for Tension-Compression-Tension Residual Stress Distribution

For residual stress distribution in Figure 5, the stress intensity factor for a circumferential crack reaches a saturated value even after a small amount of crack growth. Recently, a finite element study indicated that the saturated value of stress intensity factor can be approximated by [16]

$$K_{Ir} = 0.43\, \sigma_r \sqrt{\pi t}.$$

where σ_r is the maximum amplitude of the residual stress, usually set to the value of the yield stress (σ_y). The design thickness of the pipe is used to estimate the stress intensity factor due to residual stress.

After the stress intensity factors for the applied load and for the residual stress (K_{Ir}) are obtained, the parameter K_r for FAD analysis can be calculated:

$$K_r = \frac{K_{IC} \times FS + K_{Ir}}{K_{IC}}, \text{ where FS is the factor of safety.}$$

(2) Stress Intensity Factor for Residual Stress of Bending Type

For pipes with diameters less than 12 inches, a residual stress distribution shown in Figure 6 is assumed. The stress intensity factor solutions (K_A and K_B, respectively, at the deepest penetration and near the free surface) for a semi-elliptic surface crack bending specimen (Figure 7) [17] are used for approximation:

$$K_A = \sigma_r \frac{M}{\phi} H_2 \sqrt{\pi b}$$

$$K_B = \sigma_r \frac{M}{\phi} S\, H_1 \sqrt{\pi b}$$

where

σ_r is the maximum bending stress set to the maximum amplitude of residual stress,

$\alpha = b/a$, $\beta = b/t$,

$$M = (1.13 - 0.09\,\alpha) + \left(-0.54 + \frac{0.89}{0.2 + \alpha}\right) \beta^2 + \left[0.5 - \frac{1}{0.65 + \alpha} + 14(1 - \alpha)^{24}\right] \beta^4,$$

$$\phi^2 = 1 + 1.464\,\alpha^{1.65}\,,$$

$$S = \left(1.1 + 0.35\,\beta^2\right)\sqrt{\alpha}\,,$$

$$H_2 = 1 - (1.22 + 0.12\alpha)\beta + \left(0.55 - 1.05\,\alpha^{0.75} + 0.47\,\alpha^{1.5}\right)\beta^2\,, \text{ and}$$

$$H_1 = 1 - (0.34 + 0.11\alpha)\,\beta\,.$$

To ensure accurate solutions, the conditions, $b \le a$ and $\beta = b/t \le 0.8$, should be met. The original thickness of the pipe is used to evaluate the stress intensity factors due to the residual stress. The parameter K_r for FAD can then be calculated with K_A or K_B, whichever is larger.

Part-Throughwall Axial Cracks.

1) Stress Intensity Factor - Solution for K_r

The axial flaws in SRS piping are dominated by the hoop stress due to internal pressure (P). For a long axial flaw with depth, a, through the wall thickness, t, (Figure 8), the stress intensity factor (K_I) is given as [18]

$$K_I = \frac{2PR_o^2}{R_o^2 - R_i^2} F \sqrt{\pi a}\,,$$

where

$$F = 1.1 + A\left[4.951(a/t)^2 + 1.092(a/t)^4\right],$$

$$A = [0.125(R_i/t) - 0.25]^{0.25} \quad \text{for } 5 \le R_i/t \le 10, \text{ or}$$

$$A = [0.2(R_i/t) - 1]^{0.25} \quad \text{for } 10 \le R_i/t \le 20\,.$$

The range of applicability of the solution is $0.05 \le a/t \le 0.8$ and $10 \le R_i/t \le 20$.

When the above range of applicability is exceeded, a flat plate solution for a single edge notch specimen is used [19]:

$$K_I = \frac{PR}{t}\sqrt{\pi a}\, F\!\left(\frac{a}{t}\right),$$

where

$$F\!\left(\frac{a}{t}\right) = \sqrt{\frac{2t}{\pi a}\tan\frac{\pi a}{2t}}\;\frac{0.752 + 2.02\frac{a}{t} + 0.37\left(1 - \sin\frac{\pi a}{2t}\right)^3}{\cos\frac{\pi a}{2t}}\,.$$

The residual stress contribution is not considered in the case of axial flaws. The stress intensity factor calculated above, along with the material fracture toughness (K_{IC}), are used to evaluate the parameter K_r in the FAD analysis.

(2) Limit Load Solution - Solution for L_r

For the same crack configuration (Figure 8), the limit pressure is [18]

$$P_L = \frac{2}{\sqrt{3}} \sigma_y \frac{t - a}{R_i + a} .$$

Therefore, the parameter L_r in the FAD analysis is (Section 3.3.1) expressed as

$$L_r = \frac{(\sigma_{h,appl})\, FS}{\sigma_{h,limit}} = \frac{P}{P_L} FS ,$$

where P is the applied internal pressure.

Throughwall Axial Cracks.

(1) Stress Intensity Factor - Solution for K_r

The stress intensity factor for a throughwall axial flaw (Figure 9) due to the applied hoop stress ($\sigma_{h,appl} = P/Rt$) is [19]:

$$K_I = \sigma_{h,appl} \sqrt{\pi a} \cdot F(\lambda) ,$$

where 2a is the crack length, $\lambda = a / \sqrt{Rt}$,

$$F(\lambda) = \sqrt{1 + 1.25\lambda^2} \text{ for } 0 < \lambda \le 1, \text{ or}$$

$$F(\lambda) = 0.6 + 0.9\lambda \text{ for } 1 \le \lambda \le 5 .$$

The residual stress contribution is not considered in the case of axial flaws. The stress intensity factor calculated above, along with the material fracture toughness (K_{IC}), are used to evaluate the parameter K_r in the FAD analysis.

(2) Limit Load Solution - Solution for L_r

Based on the pipe burst experimental data, the maximum hoop stress ($\sigma_{h,limit}$) was suggested to have the form [20,21]

$$\sigma_{h,limit} = \frac{\sigma_y}{\sqrt{1 + 1.61 \frac{a^2}{Rt}}} .$$

The parameter L_r is calculated according to

$$L_r = \frac{(\sigma_{h,appl})\, FS}{\sigma_{h,limit}} = \frac{PR/t}{\sigma_{h,limit}} FS .$$

MINIMUM THICKNESS

For a particular pipe segment, the minimum wall thickness is the largest value of the wall thicknesses obtained by code stress check and FAD. Table 2 provides the basis for acceptance criteria for this carbon steel piping.

TABLE 2 Minimum Wall Thickness (t_{min}) For the Carbon Steel Piping

Line ID	Assumed Location	Material of Construction	Nominal Thickness	Thickness Requirement
36"-A	Straight Branch	A285 Gr.B	0.375"	0.146" 0.129"
30"-A	Straight Branch Branch	A285 Gr.B	0.375"	0.128" 0.161" 0.320"
24"-A	Straight Elbow Branch	A53 Gr.B or A53 Gr.A	0.25" or 0.375"	0.113" 0.168" 0.191"
24"-B	Straight Elbow	A53 Gr.A	0.375"	0.113" 0.178"
24"-C	Straight Elbow	A53 Gr.A	0.375"	0.113" 0.113"
24"-D	Straight Elbow Branch	A53 Gr.A	0.375"	0.113" 0.113" 0.113"
24"-E	Straight Elbow	A53 Gr.A	0.375"	0.113" 0.120"
24"-F	Straight Elbow	A53 Gr.B or A53 Gr.A	0.25" or 0.375"	0.113" 0.161"
18"-A	Straight Branch	A53 Gr.B	0.25"	0.075" 0.149"
16"-A	Straight Elbow	A53 Gr.A	0.375"	0.113" 0.113"
16"-A	Straight Elbow	A53 Gr.A	0.375"	0.113" 0.113"
14"-A	Straight Elbow	A53 Gr.A	0.375"	0.113" 0.113"
12"-A	Straight Elbow Branch	A53 Gr.B	0.25"	0.075" 0.075" 0.075"
12"-B	Straight Elbow	A53 Gr.B	0.25"	0.075" 0.089"
6"-A	Straight Elbow	A53 Gr.B	0.28"	0.247" 0.170"
4"-A	Straight Elbow	A53 Gr.B	0.237"	0.168" 0.071"

NOTE: The allowable wall thicknesses are to the end of pipe service life.

ACCEPTABLE FLAW SIZES

Based on a similar approach as used in calculating the minimum thicknesses reported earlier, the acceptable flaw sizes for this carbon steel piping can also be found. The pipe original thicknesses along with the ASME code-based factors of safety are used. Three types of flaws are considered:

1) Circumferential part-throughwall flaws with elliptic shape as shown in Figure 2
The flaw length along the pipe inside diameter is not limited to 5 inches as in the case of design flaw for wall thinning calculations. The flaw depth corresponding to each assumed flaw length is the variable to be determined with the FAD methodology described earlier. [Note that the variable is the pipe thickness in wall thinning calculation.]
2) Axial part-throughwall flaw with long crack length as shown in Figure 8
The flaw depth is not limited to 25% part-throughwall as in the case of design flaw for wall thinning calculations. The flaw depth corresponding to each assumed flaw length is the variable to be determined with the FAD methodology .
3) Axial throughwall flaw as shown in Figure 9
The flaw length along the pipe longitudinal direction is not limited to twice of its design thickness as in the case of design flaw or wall thinning calculations. The flaw length is the variable to be determined with the FAD methodology.

It has been shown that none of the design flaw sizes used to calculate the minimum wall thickness exceed the acceptable flaw sizes . This confirms the adequacy of the wall thinning acceptance criteria development.

ACCEPTANCE CRITERIA METHODOLOGY

An acceptance criteria methodology is a framework for periodically monitoring the conditions of piping through in-service examinations. It also includes the disposition of degraded pipe wall while maintaining safety margins against failure. The minimum wall thickness requirement, denoted by t_{min}, is obtained by assuming that the thinning is uniform due to general corrosion and that the piping loads remain unchanged after thinning. The nonuniform thinning and pitting are beyond the scope of this analysis and the technical bases can be found in Reference 4.

Measured pipe wall thickness is acceptable if it is greater than the 87.5% of the nominal (or design) thickness [9]. In the case that the pipe wall was degraded more than 87.5% of the nominal (or design) wall thickness, the values of t_{min} in Table 2 will be used for acceptance criteria for the carbon steel piping. Note that the bending moment of the piping is redistributed as a result of natural frequency shift due to the partial thinning across the span. For example, an analysis with the K-reactor -20 floor response spectra [1] indicated that a 10% frequency decrease may be translated to a 10% increase in acceleration (and piping forces) at certain frequency range [1,4]. A limit of 10% natural frequency shift in a simple beam model was proposed in accordance with the as-built piping tolerance standard accepted by the U. S. Nuclear Regulatory Commission [1,4]. Therefore, within the 10% frequency shift, Table 2 can be used directly as the wall thinning acceptance criteria for the carbon steel piping. The following two conditions should be met to ensure that the frequency shift is within the 10% limit [4]:

(i) When $\frac{t_{ave}}{t_o} \geq 80\%$, the 10% frequency shift is unconditionally met.

(ii) When $\frac{t_{ave}}{t_o} < 80\%$, $\frac{\text{Length of Thinned Portion of Pipe}}{\text{Length of Span between Pipe Supports}} \leq \frac{0.1}{1 - t_{ave}/t_o}$

where t_{ave} is the averaged wall thickness around the pipe circumference, t_o is the design or nominal pipe wall thickness.

Outside of the 10% frequency shift range, a frequency dependent force magnification factor ($F_{freq\ amp}$) must be estimated for straight pipes (Figure 1B in Reference 4). The minimum thicknesses listed in Table 2 for pipe branch locations and for pipe elbows remain the same, because $F_{freq\ amp}$ is not applicable to these locations and the ASME code-based stress intensification factors (SIF) have been considered. As a result, the values for straight pipe in Table 2 must be adjusted accordingly to reflect an increase in piping load. The acceptance criteria for the minimum wall thickness become $F_{freq\ amp} \times t_{min}^{straight\ pipe}$. Strictly speaking, only the minimum thickness derived from the postulated circumferential flaw needs to be corrected by $F_{freq\ amp}$. However, for simplicity it is proposed that

$$F_{freq\ amp} \times t_{min}^{straight\ pipe}$$

applies to all minimum thickness requirements for straight pipes ($t_{min}^{straight\ pipe}$) in Table 2.

The acceptance criteria methodology for wall thinning can be summarized in a flow chart shown in Figure 10. A thinned wall which does not meet the acceptance criteria may be acceptable, if a customized analysis is performed and the safety margins are demonstrated.

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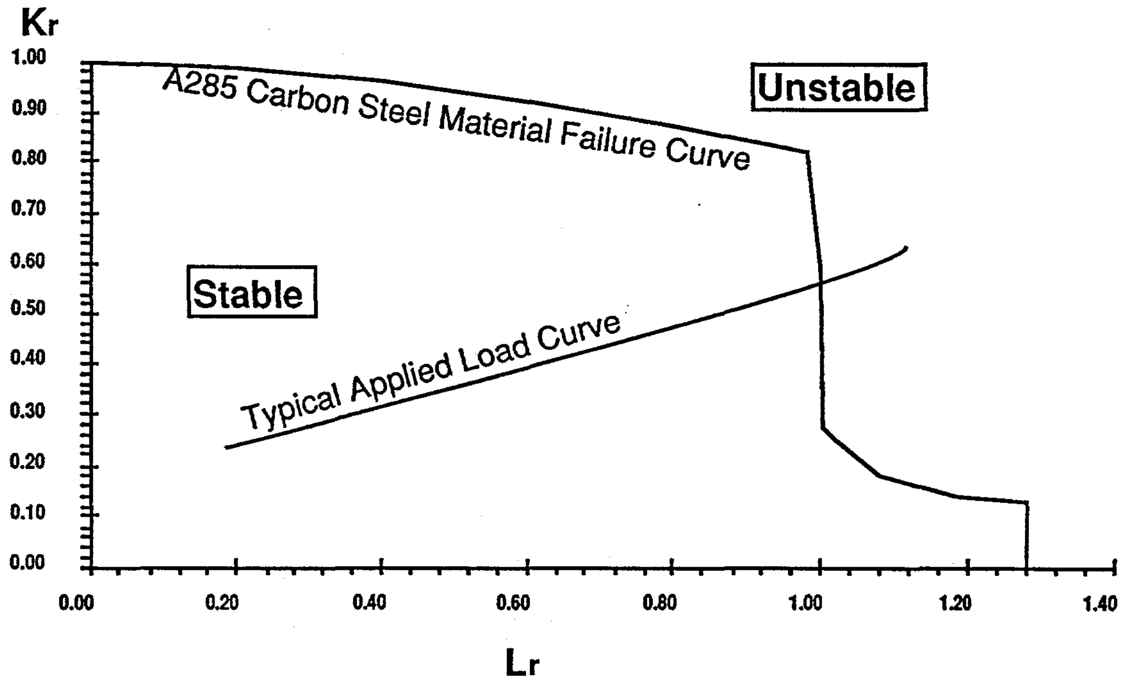

FIGURE 1. FAILURE ASSESSMENT DIAGRAM (FAD)

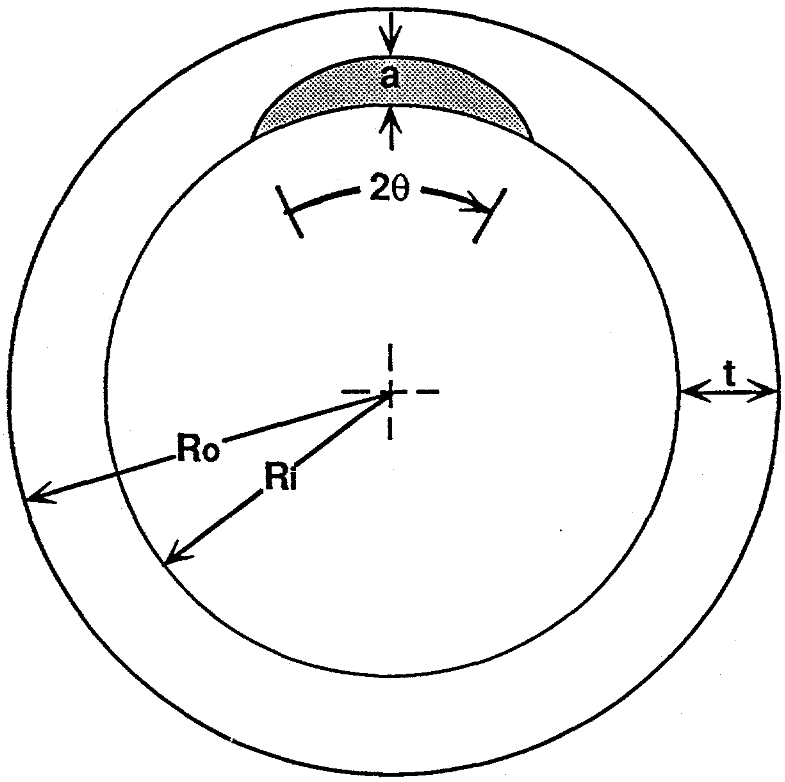

FIGURE 2 CIRCUMFERENTIAL SEMI-ELLIPTIC FLAW

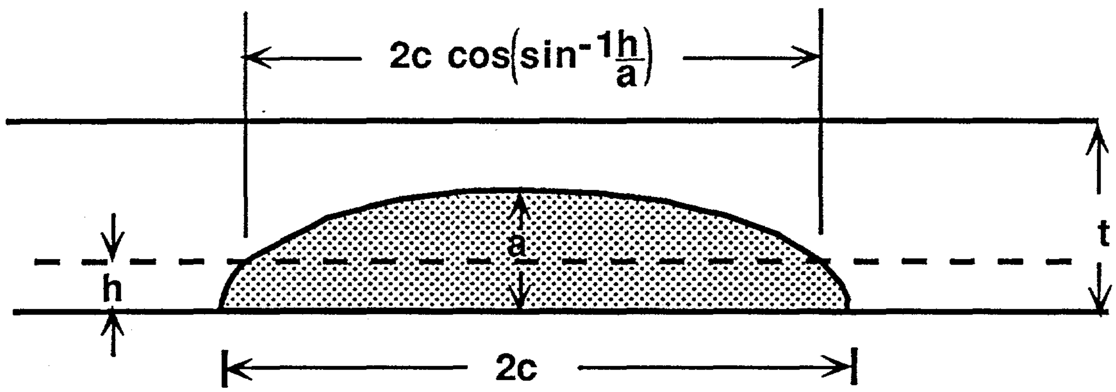

FIGURE 3 A SEMI-ELLIPTIC FLAW WITH LOSS OF SURFACE BY AN AMOUNT OF h ON THE CRACKED SURFACE

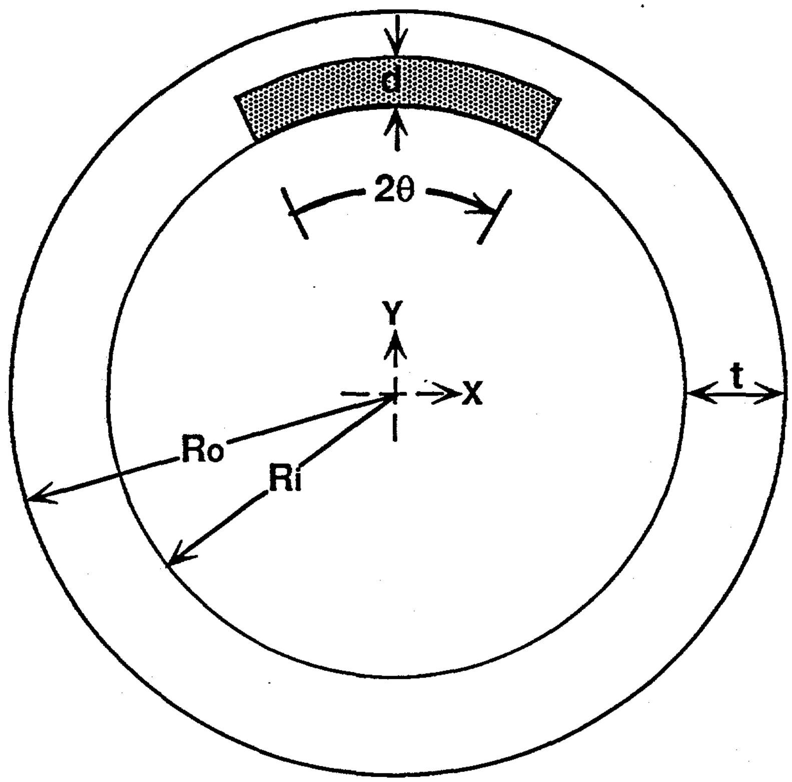

FIGURE 4 CIRCUMFERENTIAL PART-THROUGHWALL FLAW WITH UNIFORM DEPTH d.

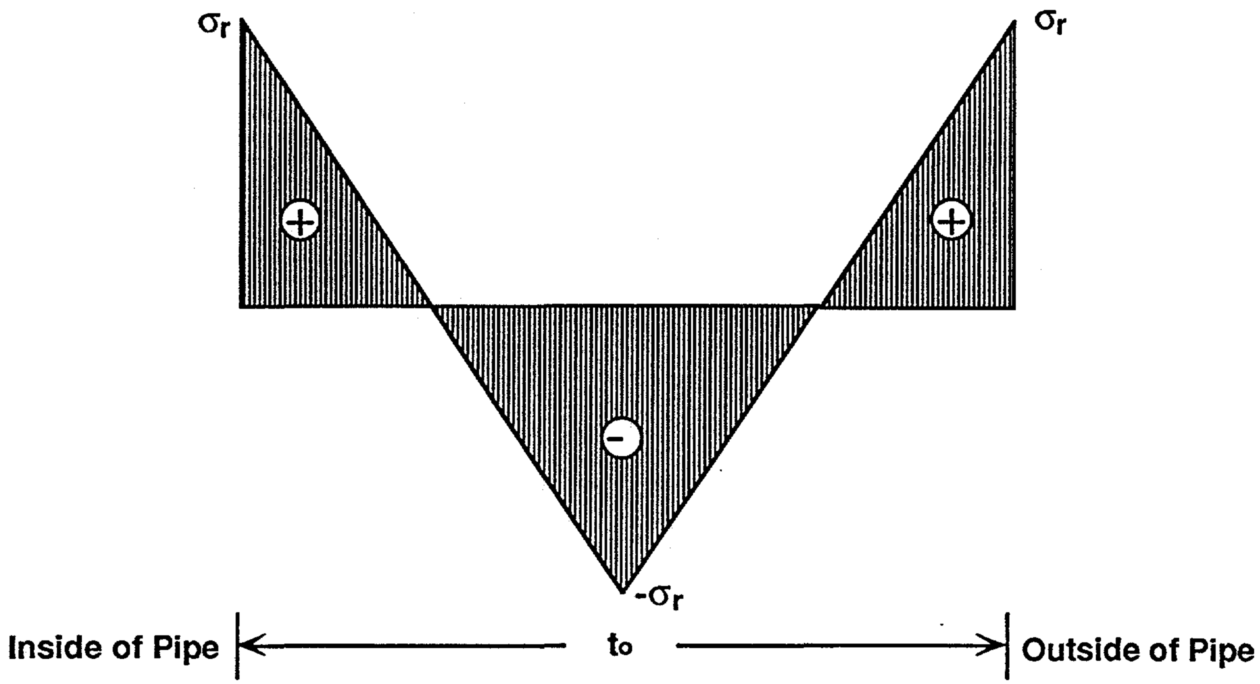

FIGURE 5 RESIDUAL STRESS DISTRIBUTION FOR PIPE SIZES ≥ 12 INCHES

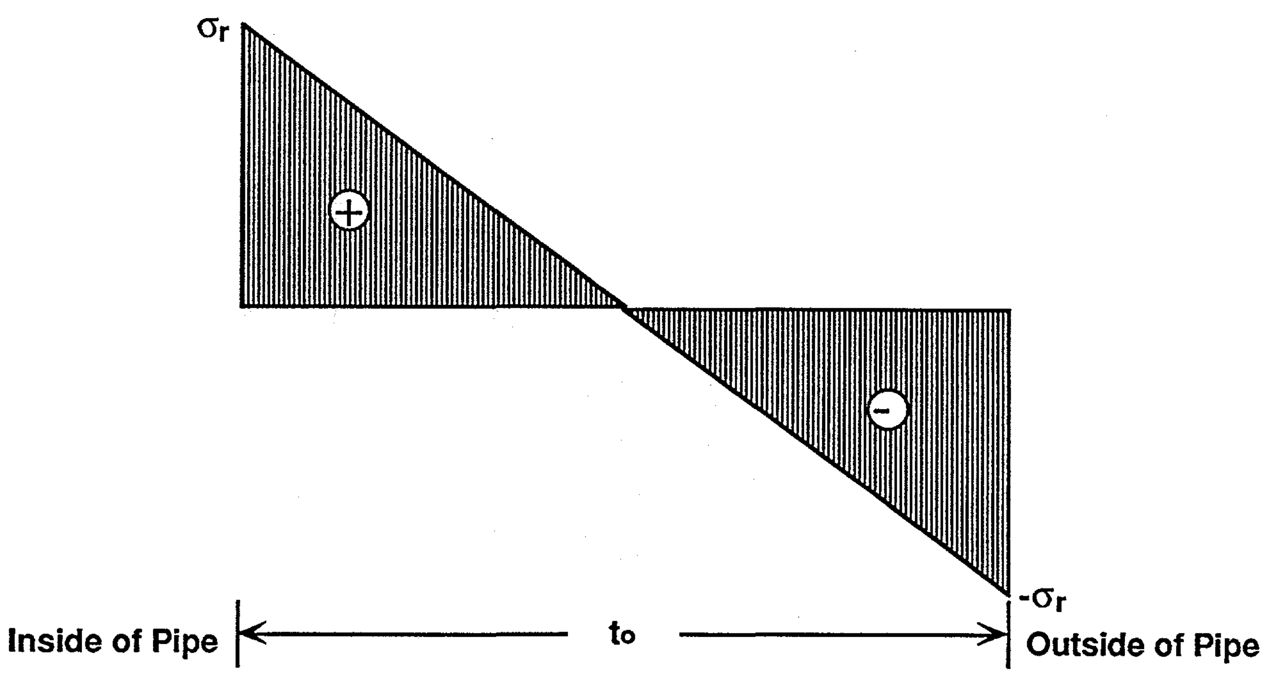

FIGURE 6 RESIDUAL STRESS DISTRIBUTION FOR PIPE SIZES < 12 INCHES

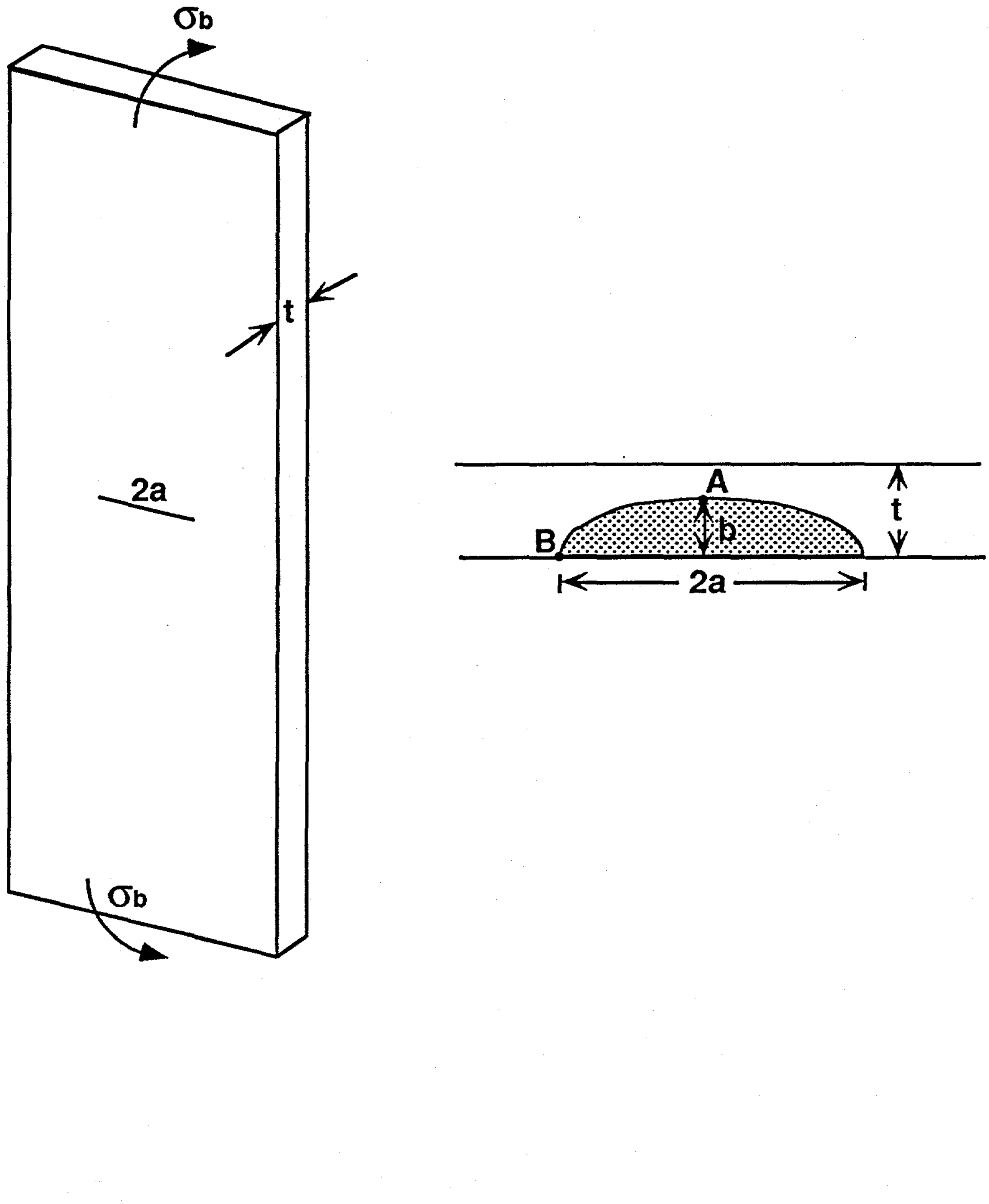

FIGURE 7 SEMI-ELLIPTIC SURFACE FLAW IN A BENDING SPECIMEN

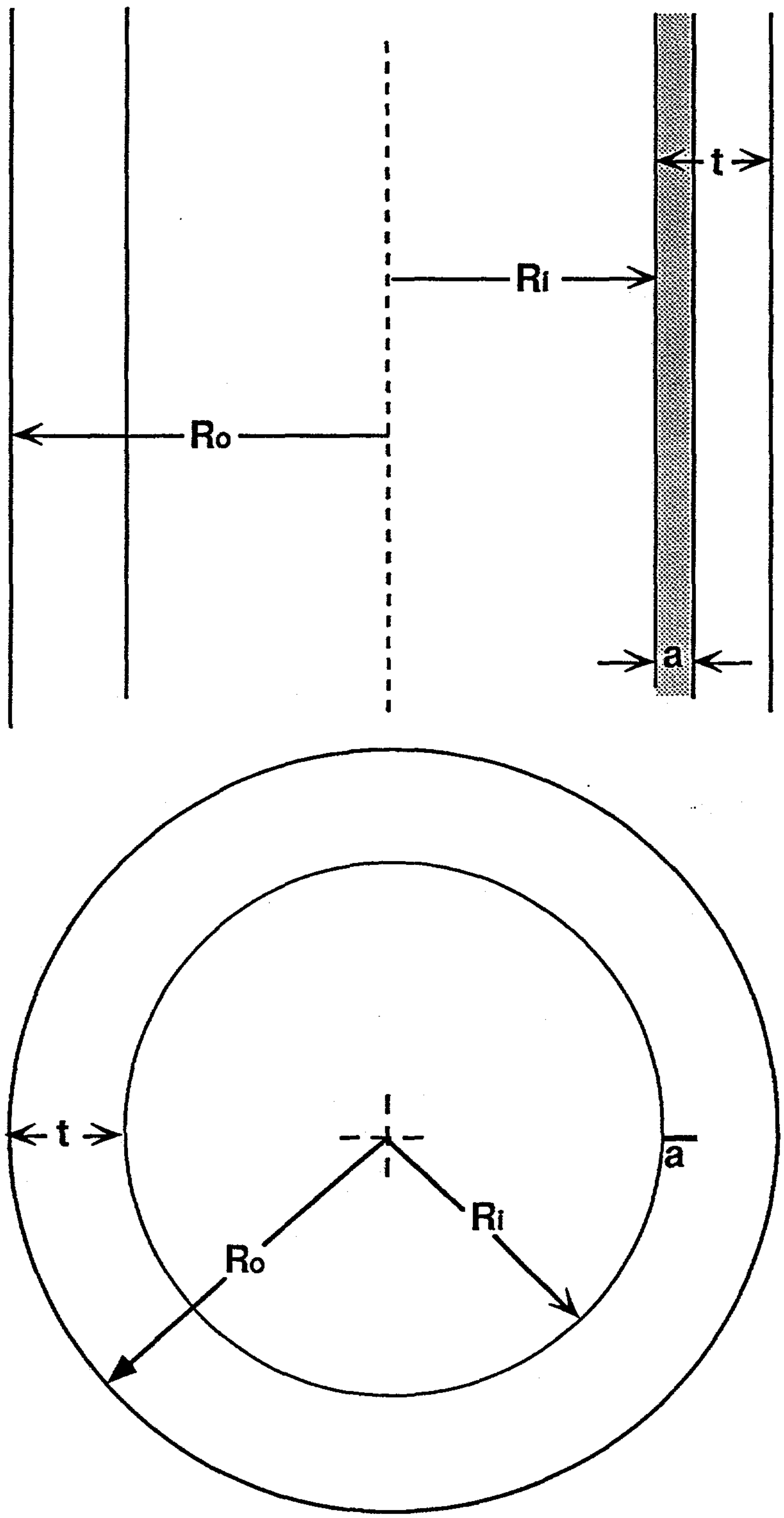

FIGURE 8 LONG AXIAL PART-THROUGHWALL FLAW WITH DEPTH a

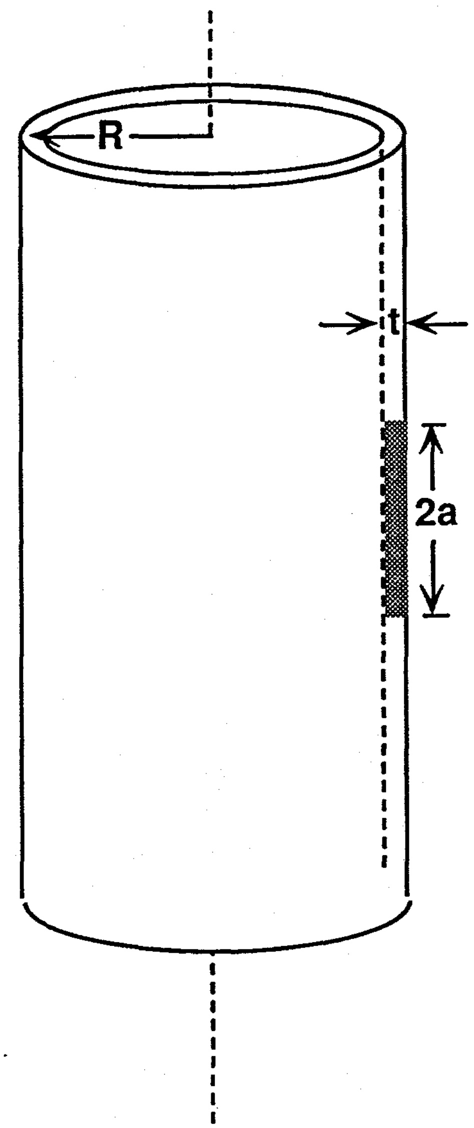

FIGURE 9 AXIAL THROUGHWALL FLAW WITH LENGTH 2a

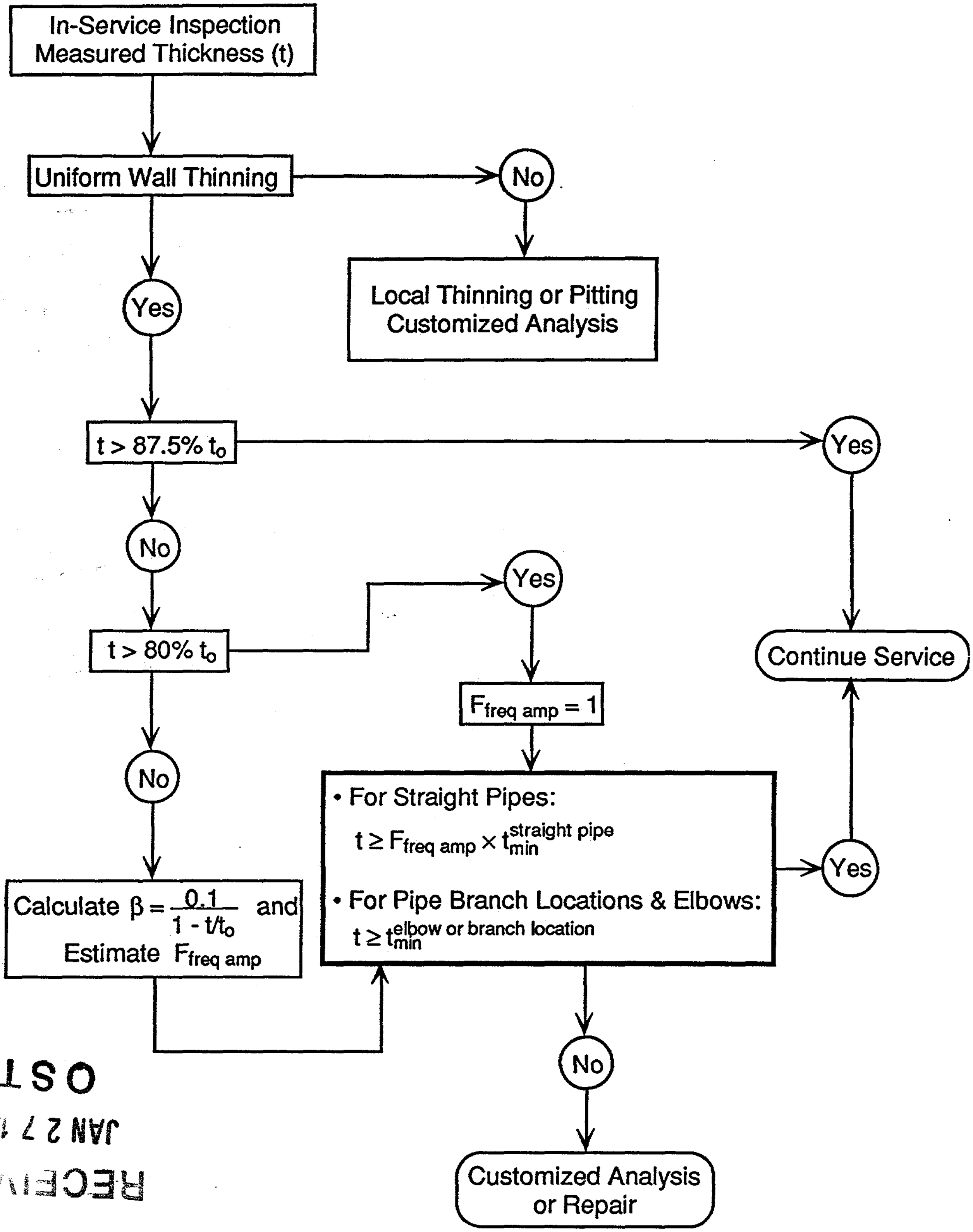

FIGURE 10 PIPE WALL THINNING ACCEPTANCE CRITERIA METHODOLOGY