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ACCEPTANCE CRITERIA FOR CORRODED CARBON STEEL PIPING CONTAINING WELD DEFECTS (U)

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ABSTRACT

Acceptance criteria for corroded low temperature, low pressure carbon steel piping containing weld defects is presented along with a typical application of these criteria. The acceptance criteria are intended to preclude gross rupture or rapidly propagating failure due to uniform wall thinning, local wall thinning, pitting corrosion and weld defects.

The minimum allowable uniform wall thickness is based on the code-of-record allowable stress and fracture criteria. Weld defects are postulated as potential sites for fracture initiation. The CEGB/R6 failure assessment diagram is used as the fracture criteria to determine the minimum allowable wall thickness.

The design of a large portion of the low temperature, low pressure piping is dominated by axial stresses. Existing local wall thinning acceptance criteria address high pressure piping where hoop stress dominates the design. The existing criteria is over conservative, in some cases, when used on low pressure piping. Local wall thinning criteria is developed to limit the axial stress on the locally thinned section, based on a reduced average thickness. Limits on pit density are also developed to provide acceptance criteria for pitted piping.

INTRODUCTION

The K Reactor at the Savannah River Site (SRS) has been in operation since 1954. Carbon steel secondary cooling water systems have experienced corrosion over the reactor's life. As a pipe corrodes, the stresses in the remaining ligament increase, reducing the structural margins of safety and increasing the possibility of gross rupture or rapidly propagating failure. Instantaneous rupture of a secondary cooling water pipe has been postulated as an accident initiator.

An inservice inspection (ISI) program began monitoring the thickness of critical lines in the early 1960s to detect thinned lines that could challenge reactor safety. Acceptance criteria in the early 1960s consisted of checking the minimum measured wall thickness against the minimum wall thickness required by the construction code for internal pressure. Normal operating bending stresses were limited by allowable span guidelines, and seismic loading was not considered by the original code of construction.

Over the past thirty years, the ISI program has evolved, increasing the number of lines inspected and the number of inspection points on each line. Additionally, the use of automated UT inspection equipment is increasing, allowing a better characterization of corroded piping. Modern piping construction codes, which include limits on bending stresses and seismic loading, are considered. As part of the recent K Reactor safety upgrades, an as built stress analysis of the secondary cooling water piping was performed, and the cooling water piping has been seismically qualified.

This paper presents acceptance criteria for corroded carbon steel piping that is consistent with (1) the current capabilities of available UT inspection equipment, and (2) the current piping construction codes, as represented by the analysis of record. Additionally, the acceptance criteria consider local buckling of a thinned section and fracture, both of which are not usually addressed explicitly by piping construction codes.

The acceptance criteria are arranged into four tiers, as shown in the following table. A section of piping that meets any one of these four tiers at the end of the next evaluation period is acceptable for continued service.

Screening Criteria:	Piping with a minimum wall thickness greater than 87.5% on the nominal wall thickness is acceptable.
Uniform Thinning:	Piping with a minimum wall thickness greater than the minimum uniform wall thickness required

by the code-of-record, local buckling criteria and fracture criteria is acceptable.

Local Thinning: Piping with an average wall thickness greater than the minimum required uniform wall thickness divided by a local thinning reduction factor is acceptable.

Pitting: Piping with a base thickness greater than the minimum required uniform wall thickness divided by a pit density reduction factor is acceptable.

DEGRADATION / DEFECT CHARACTERIZATION

System Description

The K-Reactor cooling water piping is a moderate energy piping system with pressures less than 100 psig and temperatures between 40°F and 180°F. The piping carries river water in the reactor building to heat exchangers and then back out of the building.

ASTM A53 piping and pipe fabricated from ASTM A285 plate are used in the K-Reactor cooling water piping. These systems were designed to the 1950s B31.1 code with larger diameter piping designed in accordance with the ASME Section VIII, Unfired Pressure Vessel code. Modifications to the piping system after 1981 are based on the B31.3 code. Recent as built piping stress analyses include pressure, deadweight, and seismic loading. The 1950 vintage piping codes did not include seismic loading. Thermal loading on these piping systems is insignificant.

Degradation

A systematic assessment of degradation mechanisms was conducted to determine the potential for rapidly propagating failure or gross rupture. The degradation assessment considered the effect of fluid-material compatibility, operating conditions, and service history. General attack, galvanic corrosion, pitting corrosion, and microbiologically-induced corrosion (MIC) were identified as potential degradation mechanisms. The cooling water piping is not susceptible to erosion corrosion, primarily because of the high oxygen content of the river water.

For the purposes of these acceptance criteria, damage caused by corrosion, regardless of the mechanism, is classified as either uniform thinning, local thinning, or pitting.

Weld Defect Characterization

An initial crack or defect is required to initiate fracture. Cracks in the carbon steel piping systems have not been observed during the long operating history of the SRS reactors. Two potential fracture initiators are pits and weld defects. Pits and weld defects subject to fatigue may develop cracks which could initiate fracture. An assessment of thermal and mechanical fatigue in the piping concluded that fatigue cracking was unlikely. Additionally, the largest pit observed in these systems was less than the size of observed weld defects. Thus, weld defects are conservatively postulated as crack initiation sites.

In the early 1980s, as part of the SRS L-Reactor reactivation effort, an assessment of the carbon steel piping was made to determine their suitability for continued service. Much of this piping had been installed during the plant erection in the early 1950s and is similar in construction to the piping in the K Reactor. In accordance with the codes of construction, the carbon steel piping welds were accepted by visual inspection. Radiographic examinations were not required.

Visual, radiographic, magnetic particle and destructive metallography were used to confirm the adequacy of the original pipe welds for the intended service requirements [1, 2]. The inspections did not reveal any evidence of cracking. The combination of six postulated surface defects, 1" long by 100% deep, 3"x85%, 5"x60%, 6"x45%, 9"x35% and 10"x25% bounds 99% of all of the observed weld defects. The 5"x60% flaw postulate has the largest stress intensity of the six defects and is chosen as the design flaw postulate for circumferential flaws.

Since axial flaws are shop welded under controlled conditions as opposed to field welds, the quality of shop welds is believed to be better than field welds, and the weld defect data measured during the L-Reactor reactivation effort is not applicable to axial welds. Two flaw postulates, consistent with the flaw postulates used in ASME Section XI [3], were chosen for the design axial flaw postulate.

The design flaw postulates are based on nominal wall thickness. Since the majority of the flaws observed were interior surface flaws, the relative flaw depth (flaw depth divided by the actual wall thickness) decreases when corrosion is on the inside of the pipe. Exterior corrosion removes the remaining ligament from an interior surface flaw increasing the relative flaw depth and increasing the potential for fracture. Since exterior corrosion cannot be discounted on some lines, a compromise between the two thinning assumptions is made. Wall thinning is assumed to occur equally on both the inside and outside surfaces. For the vast majority of lines, this assumption is conservative, as thinning and surface flaws are both on the inside of the pipe. The flaw length is assumed to remain unchanged.

SCREENING CRITERION

The screening criterion used in ASME Code Case N-480 is adopted, and piping with a minimum wall thickness greater than 87.5% of the nominal wall thickness is acceptable. This screening criteria is consistent with the piping fabrication tolerances.

UNIFORM WALL THINNING CRITERIA

The minimum required uniform wall thickness is the minimum thickness that satisfies (1) the code-of-record allowable stresses, (2) local buckling criteria, and (3) fracture criteria.

The piping forces for SRS low pressure, low temperature piping are typically dominated by seismic loading, which are a function of the pipe's natural frequency. As a pipe thins, the stiffness and natural frequency also decrease, possibly causing an increase in the magnitude of piping forces. One possible, but cumbersome, solution would be to reanalyze each piping system using the actual measured wall thicknesses to obtain the thinned piping forces. Another, more tractable solution, is to adopt the as-built reconciliation methodology [4], which accepts frequency shifts less than 10% and allows reanalysis using simple structural models to bound the increase in piping forces when the frequency shift exceeds 10%. The later approach is used in this analysis to conservatively increase the thinned piping forces, as required.

Analysis of Record

The minimum uniform thickness that meets the code-of-record allowable axial stress is the thickness that satisfies the following three equations for dead, dead + seismic and thermal loading.

$$\left.\begin{aligned} &\frac{P\,D_o}{4t} + \frac{0.75i\,M_a}{Z} \le S_{Allowable\ Normal} \\ &\frac{P\,D_o}{4t} + \frac{0.75i\,(M_a + M_b)}{Z} \le S_{Allowable\ Upset} \\ &\frac{i\,M_c}{Z} \le S_{Allowable\ Thermal} \end{aligned}\right\} \quad (1)$$

where P is the internal pressure, D_o is the outer diameter, t is the minimum uniform thickness, i is a stress intensification factor, Z is the section modulus, M_a, M_b and M_c are the dead load, seismic and thermal moments, and $S_{Allowable}$ is the allowable stress for a given loading, as defined by the code-of-record.

An alternate form of the pressure term in Equation 1, $\frac{P\,d_i^2}{D_o^2 - d_i^2}$, where d_i is the inside diameter, may also be used. The alternate pressure term is more accurate and provides lower stresses for thick wall piping.

Both the section modulus and stress intensification factor vary with the minimum uniform thickness. At tees, the amount of wall loss in the header is assumed to be equal to the amount of wall loss in the branch line when calculating the stress intensification factor. The left hand side of Equation 1 is approximately linear when plotted on a log-log scale, and the minimum thickness that satisfies these inequalities can be determined in several iterations.

The minimum uniform thickness that meets the code-of-record allowable hoop stress is

$$t = \frac{P\,D_o}{2\,(SE + 0.4\,P)} \quad (2)$$

where SE is the product of the allowable stress and joint efficiency.

Local Buckling

Local buckling is not a limiting failure mechanism in common pipe sizes with R/t ratios ranging between 5 and 20. Contrarily, large diameter low pressure piping may have R/t ratios near 50, and severe thinning of this piping could raise the R/t ratio to 150. Reference 9 summarizes test data which demonstrates that local buckling of straight pipe section can reduce the ultimate load capacity of A53 piping with an R/t ratio above 120. Thus, the minimum thickness is limited to preclude local shell buckling (compressive wrinkling) of thinned pipes by limiting the longitudinal compressive stress to the allowable stress for cylinders subject to axial compression.

The maximum compressive stress is conservatively assumed to be constant over the entire cross section. Bending stresses are not intensified at tees and elbows because the intensified stresses are peak stresses developed to predict fatigue life and act over a small area. ASME Section III, NC-3133.6 is used to determine the allowable compressive stress for pipes in axial compression.

Fracture Criteria

For the SRS cooling water system, the nil ductility transition temperature of archival A53 and A285 pipe is approximately equal to the minimum operating temperature. Previous fracture assessments have demonstrated that brittle fracture is not credible at the minimum operating temperatures, based on the nominal pipe wall thickness [2].

The applied stresses in the remaining ligament of a pipe increase with wall thinning. A weld defect located in a region with increased stresses could result in brittle fracture, ductile tearing, or yielding through the remaining ligament, depending on the stress, flaw size and material properties. In this analysis, the CEGB/R6 failure assessment diagram (FAD) is used to determine the minimum thickness that will not result in failure through a weld defect [5, 6].

The stress strain curves for both A53 and A285 piping are elastic-plastic below 1.5% strain, as shown in Figure 1. A material specific FAD is used in this analysis, as shown in Figure 2 and is given by

$$K_r = \frac{1}{\sqrt{\frac{E\,\varepsilon_{ref}}{L_r\,\sigma_y} + \frac{L_r^3\,\sigma_y}{2E\,\varepsilon_{ref}}}} \quad \text{for } L_r \le \frac{\sigma_f}{\sigma_y} \quad (3)$$

where ε_{ref} is the true strain corresponding to the true stress $L_r \times \sigma_y$, σ_y is the 0.2% yield stress, σ_f is the flow stress, and E is Young's modulus. Also shown in Figure 2 is an evaluation point (Kr,Lr) where

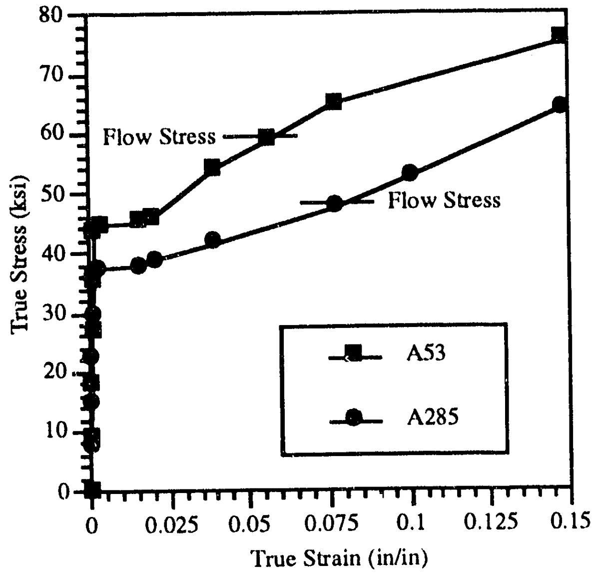

FIGURE 1 STRESS STRAIN RELATIONSHIP

$$\left.\begin{aligned} Kr &= \frac{\text{Applied Stress Intensity}}{K_{IC}} \\ Lr &= \frac{\text{Applied Stress}}{\text{Limit Load Stress}} \end{aligned}\right\} \qquad (4)$$

The applied stress intensity includes both applied and residual stresses. For the part throughwall design weld defects used in this analysis, a local limit load stress that causes plasticity across the remaining ligament is used for the limit load stress in the definition of Lr. Applied stresses in Equation 4 are multiplied by the ASME Section XI Appendix H factors of safety.

Evaluation points corresponding to progressively thinner pipe walls are determined. The last evaluation point below the FAD failure surface is the minimum wall thickness that will not result in failure through a weld defect.

LOCAL WALL THINNING CRITERIA

Existing criteria for local wall thinning are primarily based on pressure loading. Low pressure piping is dominated by axial stresses as opposed to high pressure piping which is dominated by hoop stresses. For low pressure piping, the existing local wall thinning criteria are used to preclude hoop stress failure and subsequent leakage. Additional criteria, based on the moment capacity of a thinned pipe, are used to preclude axial stress failure. A pipe with locally thinned areas is acceptable if it meets both the hoop and axial stress criteria.

Hoop Stress Criteria

ANSI/ASME B31G contains criteria to preclude rupture of piping with locally thinned areas and is based on pressure

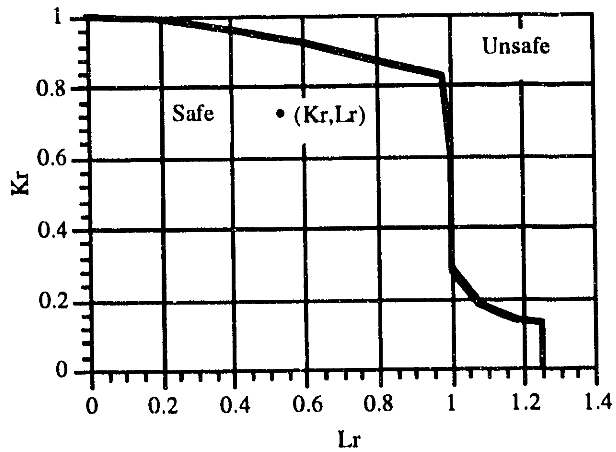

FIGURE 2 FAILURE ASSESSMENT DIAGRAM

burst tests of corroded pipelines performed by Battelle in the early 1960s [7, 8]. This criteria has been adopted in the ASME N-480 code case with an additional limitation on the amount of transverse wall thinning to preclude bending induced failure. The limitation on transverse thinning imposed in the N-480 code case is not adopted in the current local wall thinning criteria, because the current criteria explicitly checks axial stresses.

Axial Stress Criteria

Axial bending and pressure stresses are checked using the actual thinned cross sectional geometry and the code-of-record allowable stress

$$\frac{P \pi R^2}{A_{thinned}} + \frac{\text{Moment} + P \pi R^2 \overline{Y}}{Z_{thinned}} \leq S_{allowable} \qquad (5)$$

where $\overline{Y}$ is the distance between the neutral axis and the centroid, and the thinned cross sectional area is equal to $\pi\, t_{average}\, R^2$. A parametric study of piping with a sinusoidal variation in wall thickness [Appendix A] shows that the section modulus of a thinned pipe is conservatively given by

$$Z_{thinned} = \pi\, t_{average}\, R_{LTA}\, R^2 \qquad (6)$$

where R_{LTA} is given in Figure 3 as a function of the amount of thinning and the length of region below the average thickness. Assuming that the nominal pipe thickness is equal to t_{max}, then the amount of thinning, b, is typically between 0.125 and 0.7, which correspond to minimum wall thickness of 87.5% $t_{nominal}$ and 0.3 $t_{nominal}$, respectively. The curve for b=1 is included in Figure 3 for academic interest.

Combining the pressure terms in Equation 5 and simplifying,

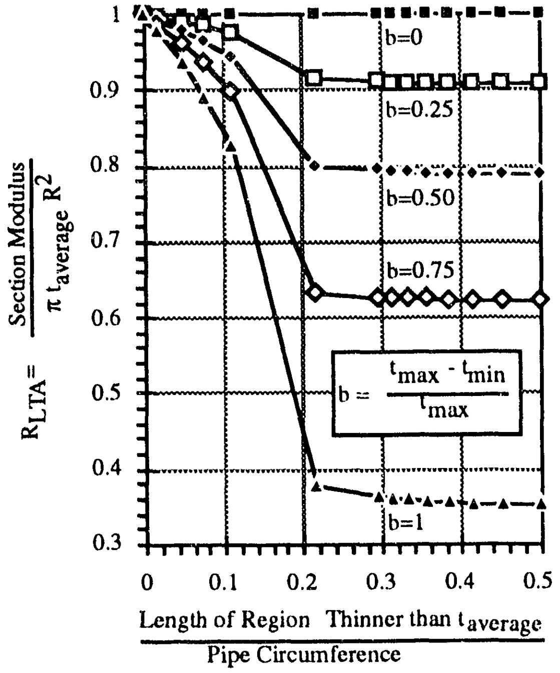

FIGURE 3 LOCAL THINNING REDUCTION FACTOR, R_{LTA}

$$\frac{P\ R}{t_{average}}\left(\frac{1}{2} + \frac{\overline{Y/R}}{R_{LTA}}\right) + \frac{Moment}{\pi\ t_{average}\ R_{LTA}\ R^2} \le S_{allowable} \qquad (7)$$

As shown in Appendix B, Equation 7 can be approximated by

$$\frac{P\ R}{2\ t_{average}\ R_{LTA}} + \frac{Moment}{\pi\ t_{average}\ R_{LTA}\ R^2} \le S_{allowable} \qquad (8)$$

The term $t_{average}\ R_{LTA}$ is an effective average thickness. The allowable axial stress criteria, local buckling criteria, and fracture criteria are satisfied on a locally thinned area if

$$t_{req\ uniform\ axial} \le t_{average}\ R_{LTA} \qquad (9)$$

or

$$t_{average} \ge \frac{t_{req\ uniform\ axial}}{R_{LTA}} \qquad (10)$$

where $t_{req\ uniform\ axial}$ is the minimum uniform thickness that meets the uniform wall thinning criteria for axial stresses.

The local stresses on the remaining ligament of a locally thinned area will be elevated, and a fatigue assessment of these elevated stresses should be performed. A fatigue assessment of the K-Reactor cooling water piping demonstrated that thermal and pressure cycling are minor, that the seismic loading only

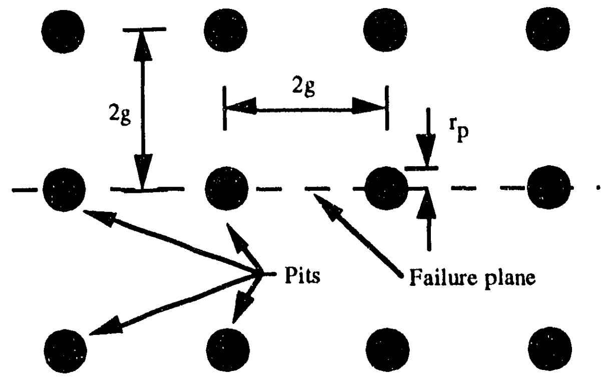

FIGURE 4 PIT ARRAY

acts over tens of cycles, and that this local thinning acceptance criteria is appropriate for the K-Reactor cooling water piping. A detailed fatigue analysis would be indicated for piping dominated by thermal expansion.

PITTING CRITERIA

Pits are conservatively assumed to be throughwall holes resulting in a reduction of load capacity due to yielding of the remaining ligament. Using the idealized rectangular pits array, as shown in Figure 4, the pit density, ρ, is given by

$$\rho = \frac{\pi\ r_p^2}{4\ g^2} \qquad (11)$$

The plastic capacity of the pitted section is $T_{pit} = N\ 2(g - r_p)\sigma_y$, while the plastic capacity of an unpitted section is $T_{pit} = N\ 2g\ \sigma_y$, where N is the number of pits on the section, 2g is the pit spacing, r_p is the pit radius and σ_y is the yield stress. Define R_{pit} as the ratio of the plastic capacity of the pitted to unpitted section and substituting in Equation 11, yields

$$R_{pit} = 1 - \sqrt{\frac{4\rho}{\pi}} \qquad (12)$$

A pitted section is acceptable if the product of the unpitted base thickness and R_{pit} is greater than the minimum required uniform wall thickness.

Triangular arrays were investigated in addition to the rectangular array, shown in Figure 4, resulting in values of R_{pit} greater than or equal to the rectangular array. Pits are randomly distributed in the field, and the actual reduction in load capacity is probably less than estimated by Equation 12.

For field applications, the pit density, ρ, can be determined by direct measurement of the pitted piping, or by conservatively estimating the average pit radius and counting the number of pits in a given sample area,

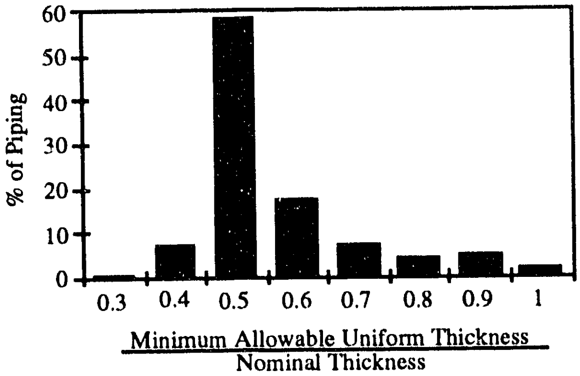

FIGURE 5 DISTRIBUTION OF MINIMUM REQUIRED UNIFORM WALL THICKNESSES

$$\rho = \pi r_{pit}^2 \frac{\text{Number of Pits}}{\text{Sample Area}} \qquad (13)$$

IMPLEMENTATION ON SRS COOLING WATER PIPING

This acceptance criteria is used to determine the minimum uniform wall thicknesses of the K-Reactor secondary cooling water piping and to disposition locally thinned areas. Figure 5 shows a histogram of the minimum required wall thickness in a typical cooling water line. Since only a very small portion of the line is highly stressed, the majority of the line has generous allowances for wall thinning. This information can be used to help prioritize future inspections and focus on areas with the smaller corrosion allowance.

A hypothetical locally thinned area in a cooling water pipe is shown in Figure 6. Since the minimum thickness is less than 87.5% of the nominal thickness, this section does not meet the screening criteria and further evaluation is required.

The minimum allowable uniform wall thickness meeting the hoop stress criteria and fracture criteria for axial flaws is 20% of the nominal wall thickness. Since the required thickness for hoop stresses is less than the minimum thickness, the uniform wall thinning criteria is satisfied for hoop stresses.

The minimum allowable thickness meeting the axial stress criteria, local buckling criteria, and circumferential fracture criteria is 55% of the nominal wall thickness. Note that the minimum wall thickness is less than the required uniform thickness, and the uniform thinning criteria is not met for axial stresses. Thus, an evaluation of a locally thinned area is indicated.

Let the transverse width of the locally thinned area, Lt in Figure 6, be half of the pipe's circumference. Using Figure 3, with the length of the region thinner than $t_{average}$ equal to 0.5 × pipe circumference and

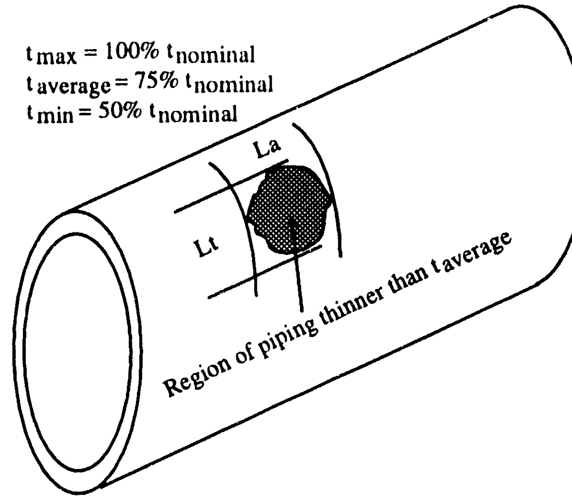

FIGURE 6 HYPOTHETICAL LOCALLY THINNED AREA

$$b = \frac{100\%\ t_{nominal} - 50\%\ t_{nominal}}{100\%\ t_{nominal}} = 0.5$$

yields $R_{LTA} = 0.78$. From Equation 10,

$$t_{average} = 75\%\ t_{nominal} \geq \frac{t_{req\ uniform\ axial}}{R_{LTA}} = \frac{55\%\ t_{nominal}}{0.78} = 0.70\ t_{nominal}$$

the local wall thinning criteria are met, and the section is acceptable.

CONCLUSION

Acceptance criteria for corroded low temperature, low pressure carbon steel piping containing weld defects are presented. The acceptance criteria protect against gross rupture or rapidly propagating failure due to uniform wall thinning, local wall thinning, pitting corrosion, and weld defects.

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APPENDIX A DEVELOPMENT OF LOCAL WALL THINNING REDUCTION FACTOR, R_{LTA}

The elastic section properties of a thinned pipe, based on thin shell theory, can be calculated from

$$A = \int dA = 2\int_0^{\pi} R\, t(\theta)\, d\theta = 2\pi\, t_{average}\, R \qquad (A.1)$$

$$A\overline{Y} = \int y\, dA = 2\int_0^{\pi} R\, t(\theta)\, R \cos\theta\, d\theta \qquad (A.2)$$

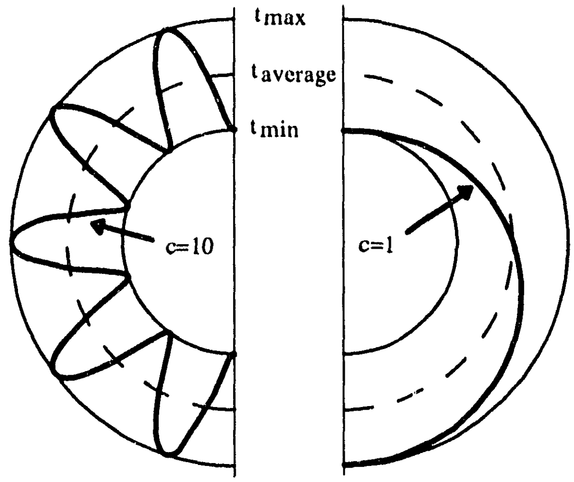

FIGURE A.1 VARIATION IN WALL THICKNESS

$$I = 2\int_0^{\pi} R\, t(\theta)\, (R \cos\theta)^2\, d\theta - A\, \overline{Y}^2 \qquad (A.3)$$

$$Z = \frac{I}{R + \left|\overline{Y}\right|} \qquad (A.4)$$

where $\overline{Y}$ is the distance from the center of the section to the neutral axis, R is the nominal radius, $t_{average}$ is the average thickness, and $t(\theta)$ is the angular variation in wall thickness. A parametric study is performed which varies the thickness as a sinusoidal function:

$$t(\theta) = t_{max}\left(1 - b\,\frac{1 + \cos(c\,\theta)}{2}\right) \text{ for } 0 \le \theta \le \pi \qquad (A.5)$$

where $b = \frac{t_{max} - t_{min}}{t_{max}}$, and c is the number of equal spaced locations around the circumference with a thickness below the average thickness. The angular variation of thickness is shown in Figure A.1 for two cases of wall thinning. The angular variation of thickness is assumed to be symmetric about the vertical axis.

Since the circumference of a pipe is πD, the length of a region with a thickness less than the average thickness is

$$L_{t<t_{average}} = \frac{\pi D}{2c} \qquad (A.6)$$

The section modulus, Equation A.4, can be rewritten in compact form as

$$Z = R_{LTA}\, \pi R^2\, t_{average} \qquad (A.7)$$

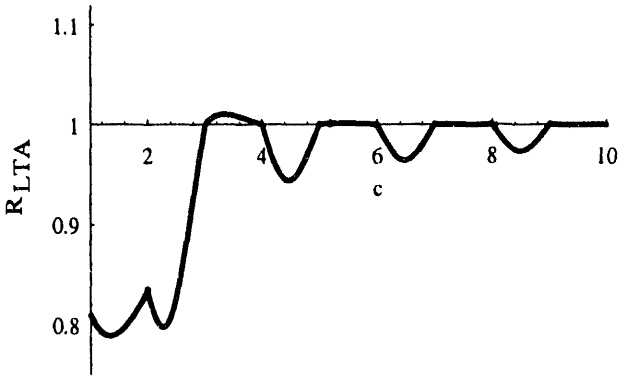

FIGURE A.2 R_{LTA}, b=0.50

where R_{LTA} is a reduction factor for locally thinned areas, and is given by

$$R_{LTA} = \frac{I}{\left[R + \left|\overline{Y}\right|\right] \pi R^2 t_{average}} \tag{A.8}$$

Equation A.8 is shown graphically in Figure A.2 for b=0.50. Note that for integer values of c greater than 2, R_{LTA} is equal to 1. The minimum value of R_{LTA} is at c=1.3, which corresponds to the thinned geometry in Figure A.3. Note that as the size of the thinned area decreases (increasing c), the effective average thickness, $R_{LTA}\, t_{average}$, approaches the average thickness, $t_{average}$. A conservative, lower bound envelope of the thin shell analytical solutions for R_{LTA} is given in Figure 3.

Thick shell solutions, with double integration of Equations A.1 to A.3, for 24" Schedule 20 (R/t≈48) and Schedule 160 (R/t≈5) pipe yield R_{LTA} within 3% of Figure A.2 for c=1.3 and b=0.5. This limited study suggests that the reduction factor for local wall thinning may also be used for thick wall piping.

APPENDIX B SIMPLIFICATION OF PRESSURE INDUCED AXIAL STRESS EQUATION

The pressure induced axial stresses are given by

$$\frac{P\,R}{t_{average}}\left(\frac{1}{2} + \frac{\overline{Y}/R}{R_{LTA}}\right) = \frac{P\,R}{2\,R_{LTA}\,t_{average}}\left(R_{LTA} + \frac{2\,\overline{Y}}{R}\right) \tag{B.1}$$

The term $R_{LTA} + 2\,\overline{Y}/R$ is shown in Figure B.1 for b=0.5 and b=1. This term is typically less than 1.10, with a peak value of 1.13 when c=1.3 and b=1.0. Recall that b=1.0 corresponds to t_{min} = 0, which is only of academic interest. Accepting up to 10% error in the pressure term, allows Equation B.1 to be approximated by

$$\frac{P\,R}{t_{average}}\left(\frac{1}{2} + \frac{\overline{Y}/R}{R_{LTA}}\right) \approx \frac{P\,R}{2\,R_{LTA}\,t_{average}} \tag{B.2}$$

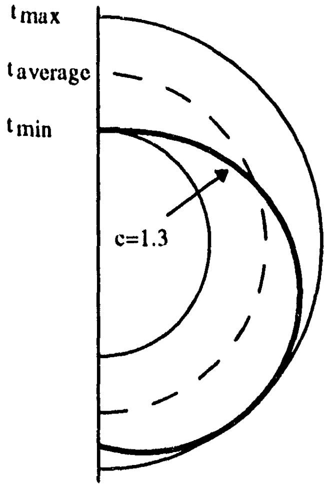

FIGURE A.3 VARIATION IN WALL THICKNESS, c=1.3

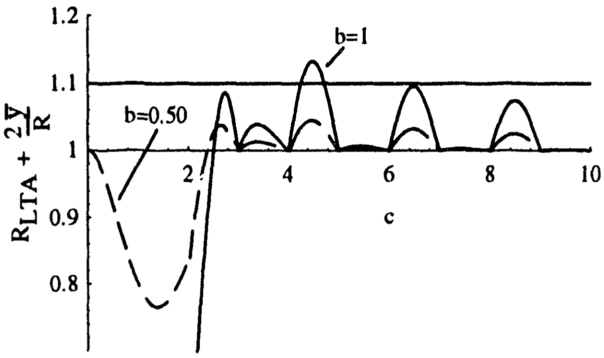

FIGURE B.1 PRESSURE MULTIPLIER

At elbows and tees, the intensified pressure term is

$$\frac{P\,R}{t_{average}}\left(\frac{1}{2} + \frac{0.75\;i\;\overline{Y}/R}{R_{LTA}}\right) \tag{B.3}$$

For intensification factors in the 2-3 range and moderate wall thinning, b ≤ 0.5, then the approximation will be accurate to about 10%. For larger intensification factors the accuracy of this approximation degrades. The accuracy of this approximation is a secondary issue for low pressure piping systems, where the pressure term represents less than 10% of the allowable stress. Equation B.3 can be used as the pressure term for high pressure systems. Note, regardless of the pressure, as the size of the locally thinned area becomes smaller (large c), then the distance to the neutral axis approaches zero and the approximation is valid.

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