Acceptance Criteria for Structural Evaluation of Erosion/Corrosion Thinning in Carbon Steel Piping

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ABSTRACT

This paper provides an overview of acceptance criteria recently developed for evaluation of carbon steel piping erosion/corrosion wall thinning. Criteria are based on Code design requirements. They define the depth and extent of wall thinning which can be safely left in service.

INTRODUCTION

Wall thinning in carbon steel pipe due to erosion/corrosion has resulted in several pipe ruptures in high–energy systems [INPO, 1987]. These failures have lead to extensive efforts by the nuclear industry to understand the specific causes of wall thinning, identify potentially susceptible locations, carry out inspections and repair/replace piping and components as required [Virginia Power Company, 1987; EPRI NP–6066, 1988; EPRI Workshop, 1987; USNRC Bulletin, 1987].

Small variations in wall thickness are expected in all piping and should be acceptable without further evaluation. At the other extreme, piping and components with extensive wall thinning should be immediately repaired or removed from service. Between these two extremes are degrees of wall thinning which will require further evaluation. These evaluations could lead to replacement, repair or continued monitoring depending on the nature and extent of thinning along with the structural requirements of the component.

The acceptance criteria described in this paper were originally developed by the Electric Power Research Institute (EPRI) [EPRI NP–5911SP]. For the most part, these criteria are based on existing piping design Code requirements. While erosion/corrosion wall thinning is not explicitly addressed in these Codes, design rules do address the geometries and loading conditions which are typical of wall thinning. Consequently, appropriate guidance has been deduced from these rules. In a couple of cases, guidance from one Code has been extracted and applied to piping designed to a different Code. This was done where it was felt that such extrapolations were reasonable and appropriate.

Subsequent to the EPRI wall thinning acceptance criteria development effort, ASME Section XI established a Special Working Group (SWG) on Pipe Wall Thinning. This SWG is considering wall thinning acceptance standards based on the EPRI work with some relatively minor differences. The criteria discussed here include the additional simplifying and conservative assumptions proposed and now being considered by the Section XI SWG.

EVALUATION OVERVIEW

Figure 1 provides a flow chart describing the approach for evaluation of erosion/corrosion thinning. A three–step evaluation process is provided which includes 1) a screening comparison against the nominal wall thickness, 2) a determination of and comparison to the actual minimum pipe wall requirements, and 3) an evaluation of the extent and depth of local thinning. The evaluation process begins with a measurement and/or prediction of the remaining wall thickness. Referring to Figure 2, this thickness is referred to as t_p and is the minimum predicted wall thickness of the component at the end of the period for which it is being evaluated.

The piping predicted wall thickness is first compared with the component nominal wall thickness (t_{nom}). This thickness value should be readily available from design documentation such as drawings, purchase specifications or materials certifications. General requirements for carbon and alloy steel pipe specify permissible variations in wall thickness. For seamless and welded product forms, the wall thickness at any point may be less than the specified nominal thickness by up to 12.5%.

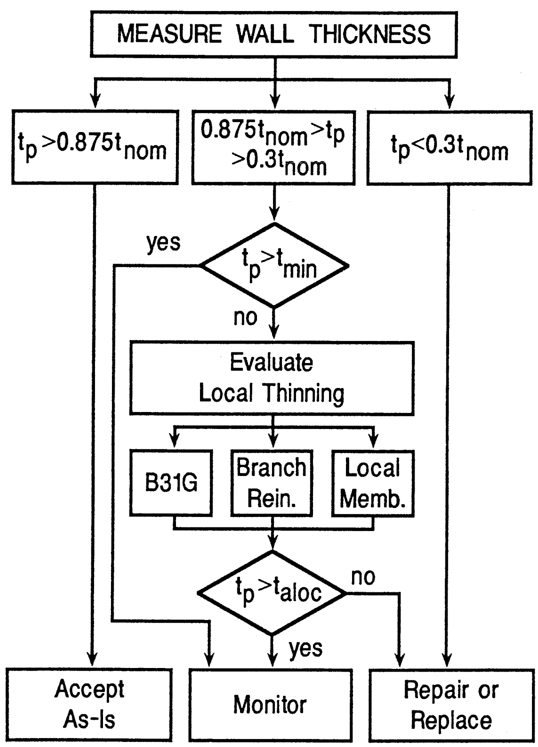

Figure 1. Evaluation of Wall Thinning Logic Diagram

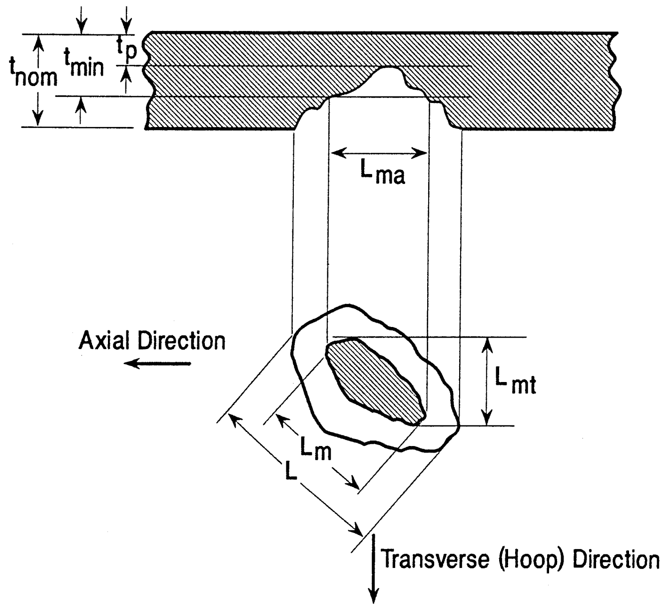

Figure 2. Schematic of Depth and Extent of Wall Thinning

If the predicted wall thickness is within the specified wall thickness tolerance ($t_p > .875\ t_{nom}$) no further evaluation is needed. The component is acceptable and future inspections are unnecessary unless other evidence suggests that erosion/corrosion may still be of concern. At the other extreme, if the predicted wall thickness is only a small fraction of the nominal wall thickness, it would be prudent to repair or replace the component without further evaluation. Specifically, if the measured wall thickness is less than say 30% of the nominal wall thickness ($t_p < .30\ t_{nom}$), repair or replacement is recommended.

For intermediate cases, where the predicted wall thickness is less than nominal wall thickness minus the manufacturing tolerance but greater than 30% of the nominal wall thickness, more detailed evaluation is recommended.

A key parameter needed for the second step of the evaluation is the component minimum wall thickness (t_{min}). t_{min} is a design parameter which depends on the Code of construction, material properties and piping pressure and bending loads. If the predicted wall thickness (t_p) is below manufacturing tolerance, but greater than the design minimum ($t_p > t_{min}$) no further evaluation is needed but monitoring of this location is recommended.

Thus far, the evaluation process has been concerned with the depth of wall thinning and not the extent. In some cases, it may be acceptable to have predicted wall thicknesses less than the design minimum and still maintain piping structural margins. These are cases in which the extent of thinning is limited and the resulting stress magnification can be demonstrated to be "local."

In the third step of the evaluation, three criteria are considered for evaluating local wall thinning. Paragraph NB–3200 of Section III of the ASME Code [ASME, 1983] provides a definition for local membrane stress and gives acceptance criteria for wall thickness less than the design minimum. Another approach for evaluating the depth and extent of local wall thinning is based on ANSI/ASME B31G [ANSI, 1985] pipeline axial corrosion acceptance criteria. These criteria apply if the extent of thinning is limited in the transverse direction. The third approach, based on branch reinforcement design rules, may be useful if the nominal wall thickness is larger than the minimum thickness. If none of the local wall thinning criteria can be satisfied, repair or replacement is indicated.

Brief discussions of how to calculate the minimum wall thickness (t_{min}) and allowable local wall thickness (t_{aloc}) are provided in the following sections.

MINIMUM WALL THICKNESS

Design requirements for nuclear power plant piping are specified in various Code documents. The particular Code or Codes depend on the date of construction, safety classification and other licensing commitments. The design requirements include both hoop and axial stress limiting equations.

The governing equation for t_{min}, is generally the equation for hoop stress due to internal pressure. This equation is a variation of the standard expression for hoop stress in a pressurized, thin–wall cylinder, with the allowable stress from the particular Code inserted, and the equation solved for wall thickness. As described in the governing Code, two additional terms provide small corrections to this basic equation to account for multi–axial state of stress and wall loss due to forming or other mechanisms.

Typically, a design pressure is specified for each system (or portions of systems), which is somewhat higher than the maximum pressure expected to occur during normal plant operation and anticipated transient events. This pressure is used in the t_{min} hoop stress equation to determine the required wall thickness.

The design codes also put restrictions on axial stress, and these restrictions may control t_{min}. The equations governing axial stresses include terms for axial stress due to pressure and primary bending loads. In addition, the original design requirements may have required that occasional or unexpected conditions be evaluated, with an associated increase in stress allowable. The axial stress equation(s) should be checked using t_{min} calculated from the hoop stress equation. If the axial stress requirements can not be satisfied, t_{min} must be increased until the axial stress requirements are met.

The equations for calculating minimum wall thickness, t_{min}, are the same for both straight pipe segments and for components such as elbows and tees. Both the hoop stress and axial stress equations need to be satisfied. The component geometry effects on t_{min} are accounted for in the geometric stress indices and stress intensification factors. These factors appear in the axial stress equations and sometimes result in the calculated t_{min} for a component exceeding that calculated for straight pipe.

The need to confirm that t_{min} satisfies the design Code axial stress requirements poses a problem if bending loads or stresses are not known. Further, not having bending load information may be more the rule than the exception. The following approachs could potentially be used to address this problem:

1. Calculate t_{min} from the appropriate hoop stress equation and use this value in the axial stress equations for the applicable Code to calculate how much bending load can be tolerated at the location of concern. Estimate piping loads to show that expected primary bending loads are less than this value.

2. Assume that t_{min} equals .875 t_{nom} and proceed with local wall thinning evaluations. The inherent assumption in this approach is that the design process guarantees that .875 t_{nom} satisfies both the hoop stress and axial stress equations.

3. Perform a piping analysis to determine bending loads.

The equations governing t_{min} as well as the equations for allowable local thinning depend only on primary piping loads. These typically include pressure, dead weight and operating basis seismic loads (OBE). The focus on primary loads is justified in that rupture of ductile piping materials can only occur with significant deformation which cannot typically be produced by secondary or strain–controlled loads (e.g. thermal expansion).

ALLOWABLE LOCAL WALL THICKNESS

If the minimum wall requirements of Figure 1 can not be met, three local thinning options are available for evaluation of allowable extent of thinning below t_{min}. These include consideration of allowable axial corrosion, branch reinforcement, or local membrane stress.

Axial Corrosion

ANSI/ASME B31G, 1984 Edition [ANSI, 1984] provides guidance for determining the strength of corroded pipe lines. This guidance is based on the work of Kiefner and Duffy performed for the American Gas Association [Kiefner and Duffy, 1971; Kiefner, 1974]. Kiefner conducted a series of experiments with corroded pipe and demonstrated that the burst pressure could be represented (for ferritic and austenitic pipe corrosion) by simple empirical expressions. He found that, in the absence of bending stresses, the extent of thinning in the circumferential direction did not change the limiting burst pressure. For the case of nuclear plant piping, where bending stresses may be significant, the extent of circumferential thinning must be limited.

Curve 1 in Figure 3 is used to determine the local allowable wall thickness, t_{aloc}, as a function of axial extent of local thinning below t_{min} based on ANSI/ASME B31G. To use this curve the extent of thinning below t_{min} in the hoop or transverse direction must be less than $\sqrt{Rt_{min}}$ where R is the component outside radius.

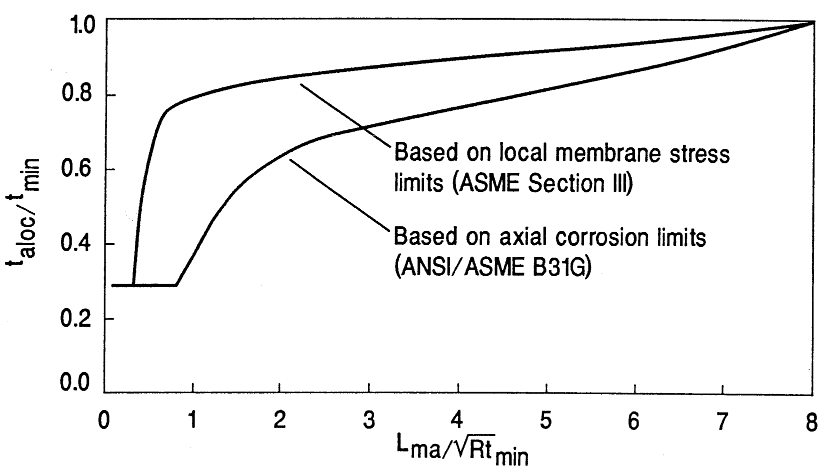

Figure 3. Allowable Depth and Length of Locally Thinned Area

Branch Reinforcement

The different versions of the Code used to design nuclear piping all provide guidelines for design of branch connections. The guidelines include rules for compensating for the material lost in making the branch opening such that overall structural capacity of the pipe is maintained. These rules include the amount of material that must be added and its location and distribution relative to the opening. Situations where no reinforcement is needed are also defined.

Figure 4 shows conceptually how branch reinforcement rules can be used to evaluate local wall thinning. First, one can conservatively estimate the area associated with this loss as:

$$A_1 = L_m \, (t_{min} - t_p) \tag{1}$$

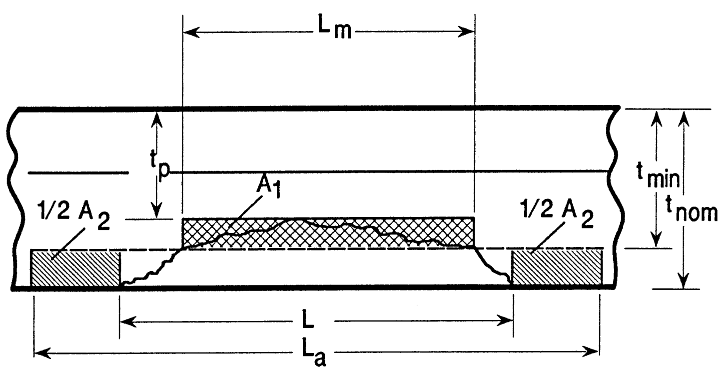

Figure 4. Concept of Area Reinforcement for Local Thinning Wall Loss

Branch reinforcement rules require that this area loss be compensated with excess material distributed uniformly around the periphery of the loss region, within certain limits of reinforcement (L_a). For the case of wall thinning, this area would be:

$$A_2 = (L_a - L)\,(t_{nom} - t_{min}) \tag{2}$$

The excess or compensating material must be located near the loss region such that L_a is less than a given amount depending on the design Code. Using equations (1) and (2), and the requirement that Structural Integrity of the material over the thinned region must be maintained together with certain simplifying assumptions, the local allowable pipe wall thickness, t_{aloc}, can be determined from the following:

$$\text{if } L_m \leq 2.65\sqrt{Rt_{min}} \text{ and } t_{nom} > 1.13\, t_{min} \tag{3}$$

then use the larger of the following:

$$t_{aloc}/t_{min} \geq \frac{1.5\sqrt{Rt_{min}}}{L}\left[1 - \frac{t_{nom}}{t_{min}}\right] + 1 \tag{4}$$

$$\text{or } \; t_{aloc}/t_{min} \geq 0.353\, L_m / \sqrt{Rt_{min}} \;, \tag{5}$$

Local Membrane Stress

The t_{min} equations in the various codes depend on general membrane stress limits, assuming that t_{min} prevails over the entire pipe. For cases in which the thickness is reduced only over a localized region of the pipe, a less conservative requirement is appropriate. Although piping design codes do not specifically address such local thickness effects, the ASME Sec. III, Class 1 piping design rules permit use of alternative rules for design by analysis, contained in ASME Sec. III, NB–3200 [ASME, 1983]. These rules allow a local primary membrane stress limit of 1.5 S_m on stress provided that the stress does not exceed 1.1 S_m over a distance $\sqrt{Rt_{min}}$. This limit is illustrated schematically in Figure 5.

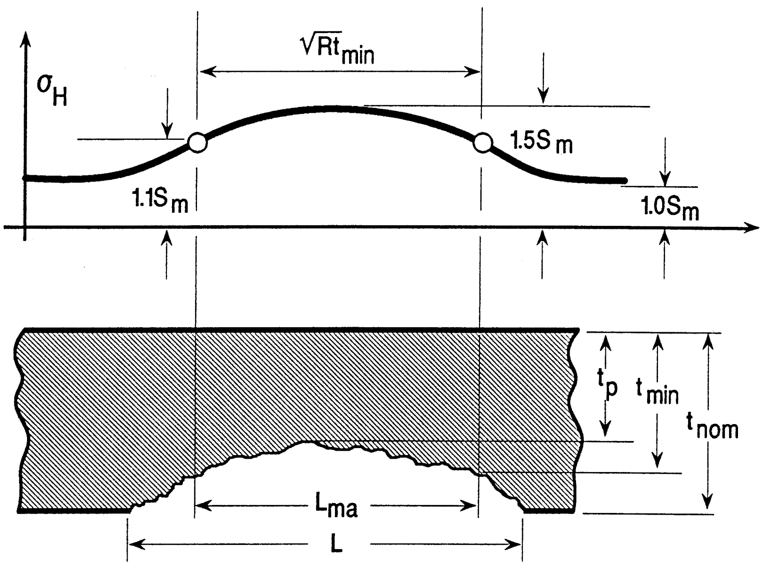

Figure 5. Definition and Stress Limits for Local Membrane Stress Per ASME Section III, NB–3200 [ASME, 1983]

Although the local membrane stress rule is only strictly applicable to ASME Section III, Class 1 piping, it is felt that application of the rule to piping systems designed to other Codes is technically justified, as long as the allowable stress value used in applying it is kept equal to that of the original Code of construction.

With the conservative assumption that thinning extends completely around a pipe or component in the hoop direction, curves defining an acceptable depth and axial extent of local thinning based on this local membrane stress requirement have been developed for piping designed to different Codes (EPRI NP–5911SP, 1988).

A bounding curve for determining t_{aloc} is shown as curve 2 in Figure 3. Additional limits on axial stress, which depend on the Code used in design of the piping, also apply. These additional limits consider the bending loads which exist and must be met to assure that the axial stresses in the thinned area satisfy the previously discussed axial stress equations.

CONCLUSIONS

A three–step evaluation process was developed for evaluation of erosion/corrosion thinning in carbon steel piping. The three–step process included 1) screening to determine if further evaluation is warranted, 2) comparison of general wall thinning with design minimum wall thickness requirements, and 3) evaluation of local wall thickness less than the design minimum based on three alternative acceptance criteria.

The acceptability of local wall thinning below t_{min} is based on axial corrosion, branch reinforcing, or local membrane stress rules. Figure 6 shows the logic used to select the appropriate local wall thickness evaluation method. For actual application, pc–based software was developed for providing rapid evaluations of specific situations, and for performing parametric evaluations in preparation of actual piping inspections.

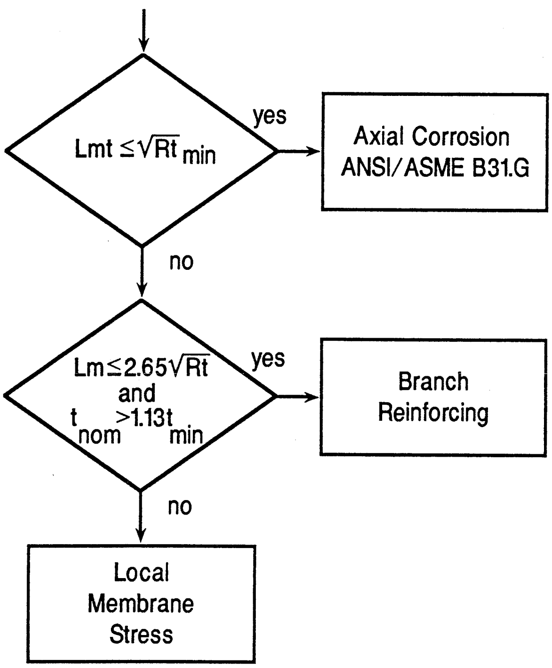

Figure 6. Local Wall Thinning Evaluation Selection Logic

The codification of these evaluation and acceptance criteria has in some instances required simplifications that were necessarily conservative. Additional margins are potentially possible if evaluations are based on the original thinning criteria (EPRI NP–5911SP).

ACKNOWLEDGEMENT

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REFERENCES

ANSI/ASME B31G, "Manual for Determining the Remaining Strength of Corroded Pipelines", 1984 Edition.

ASME Boiler and Pressure Vessel Code, Section III, "Nuclear Power Plant Components", 1983 Edition.

Electric Power Research Institute Workshop on Erosion–Corrosion of Carbon Steel Piping, Washington, D.C., April 14 and 15, 1987.

Electric Power Research Institute, "Utility Response to NRC Bulletin 87–01, Thinning of Pipe Walls in Nuclear Power Plants", EPRI NP–6066 (RP 2057–7), October, 1988.

Electric Power Research Institute, "Acceptance Guideline for Structural Evaluation of Erosion/Corrosion Thinning in Carbon Steel Piping,"EPRI NP–5911SP, (RP 1757–61), April, 1988.

INPO, "Pipe Failures in High–Energy Systems Due to Erosion/Corrosion," INPO–SOER 87–3, March, 1987.

Kiefner, J.F. and Duffy, A.R., "Summary of Research to Determine the Strength of Corroded Areas in Line Pipes," NG–18 Paper No. 39, Battelle Columbus Laboratories., July, 1971.

Kiefner, J.F., "Corroded Pipe: Strength and Repair Methods," Preceding of the 5th Symposium on Line Pipe Research, Houston, November 20–22, 1974, American Gas Association, Catalogue No. L30174.

Virginia Power Company, "Surry Unit 2 Reactor Trip and Feedwater Pipe Failure Report," Rev. 0, January, 1987.

U.S. Nuclear Regulatory Commission (USNRC) Bulletin 87–01, "Thinning of Pipe Walls in Nuclear Power Plants," July, 1987.