Proceedings of PVP2006-ICPVT-11
2006 ASME Pressure Vessels and Piping Division Conference
July 23-27, 2006, Vancoucer, BC, Canada

PVP2006-ICPVT-11-93278

SUPPLEMENTARY TECHNICAL BASIS FOR ASME SECTION XI CODE CASE N-597-2

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ABSTRACT

Section XI of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code provides rules and requirements for maintaining pressure boundary integrity of components, piping, and equipment during the life of a nuclear power plant. Code Case N-597-2 of Section XI, *Requirements for Analytical Evaluation of Pipe Wall Thinning*, provides evaluation procedures and acceptance criteria to justify continued operation of Class 1, 2 and 3 piping items subjected to wall thinning by a mechanism such as flow-accelerated corrosion. The acceptance criteria ensure that margins equivalent to those of the ASME B&PV Code are maintained. The technical basis for Code Case N-597-2 was previously presented at the *1999 ASME Pressure Vessels and Piping Conference*. Since then, the ASME Section XI Working Group on Pipe Flaw Evaluation has identified the need for further explanation of the technical basis for the Code Case, such as the procedures for evaluation of wall thickness less than the Construction Code Design Pressure-based minimum allowable wall thickness, t_{min}. This paper provides an additional description of the Code Case technical basis and validation against experimental and historic wall thinning events.

NOMENCLATURE

a = depth of an axial flaw
A = reinforcement area required for a Class 1 pipe under internal pressure in accordance with rules in Section III of the ASME B&PV Code
A_i = predicted inside area of the cross-section of the pipe
A_o = total cross-sectional area of the pipe based on nominal outside diameter
A_p = predicted metal cross-sectional area of the pipe
A_{rein} = reinforcement area required for a Class 2 or 3 pipe under internal pressure in accordance with rules in Section III of the ASME B&PV Code
B = parameter used to calculate maximum allowable length of an axial flaw in ANSI/ASME B31G
d = distance from the center of a local thinned area defining the limits of reinforcement for Class 2 and 3 piping in accordance with the Construction Code
D_o = nominal outside diameter of the piping item
f = stress range reduction factor for cyclic conditions for Class 2 and 3 piping
i = stress intensification factor for Class 2 and 3 piping
i_0 = stress intensification factor based on the design-basis geometry of the piping item
k = constant used to describe the assumed linear increase in stress intensification factor i
L = maximum extent of a local thinned area with $t_p < t_{nom}$
L_A = distance used to define limits of reinforcement for Class 1 piping in accordance with rules in Section III of the ASME B&PV Code
L_{ax} = maximum allowable length of an axial flaw from ANSI/ASME B31G
L_m = maximum extent of a local thinned area with $t_p < t_{min}$
$L_{m(a)}$ = axial extent of a local thinned area with $t_p < t_{min}$
$L_{m(t)}$ = transverse (circumferential) extent of a local thinned area with $t_p < t_{min}$
M_b = bending moment
n = number of load cycles
N = number of allowable load cycles
N' = number of allowable load cycles corresponding to an assumed linear increase in stress intensification factor i
N_0 = number of allowable load cycles based on the as-installed geometry of the piping item
P = Design Pressure
R = mean radius of the piping item based on nominal outside radius and nominal wall thickness
R_{min} = mean radius of the piping item based on nominal outside radius and t_{min}
s = stress range due to cyclic loading
s_0 = stress range due to cyclic loading based on the design basis geometry of the piping item

S = maximum allowable stress at the service temperature for Class 2 and 3 piping
S_A = allowable stress range for expansion stresses for Class 2 and 3 piping
S_b = nominal longitudinal stress due to bending moments
S_c = basic allowable stress for the material at minimum (cold) temperature
S_h = basic allowable stress for the material at maximum (hot) temperature
S_m = design stress intensity for the material at the service temperature for Class 1 piping
S_p = nominal longitudinal stress due to internal pressure
S_{TE} = sustained plus expansion stress range for Class 2 or 3 piping
t = wall thickness
t_{aloc} = allowable local wall thickness for a local thinned area
t_b = uniform thickness required by the Construction Code to withstand sustained and occasional bending loadings in the absence of internal pressure, thermal expansion and anchor movement loadings
t_{min} = Construction Code Design Pressure-based minimum allowable wall thickness of the piping item, exclusive of corrosion allowance
t_{nom} = nominal wall thickness of the piping item
t_p = predicted distribution of wall thickness at the end of the evaluation period
$t_{p,min}$ = minimum predicted wall thickness at the end of the evaluation period
y = factor required by the applicable piping Construction Code in the calculation of t_{min}, and is equal to 0.4
Z_{min} = predicted minimum section modulus of the thinned section of pipe
δ = nominal distance between the center of the pipe and the neutral axis of the thinned pipe section
σ_b = through-wall bending stress in an idealized circular plate due to internal pressure

INTRODUCTION

Section XI of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code [1] provides rules and requirements for maintaining pressure boundary integrity of components, piping, and equipment during the life of a nuclear power plant. The term pressure boundary integrity includes prevention of leakage from the reactor coolant system, as well as structural integrity in terms of prevention of rupture or burst of the pressure boundary. The first Code Case that provided evaluation procedures and acceptance criteria for Class 1, 2, and 3 piping items subjected to flow-accelerated corrosion was Code Case N-480 of Section XI, *Examination Requirements for Pipe Wall Thinning Due to Single Phase Erosion and Corrosion* [2], which was first published in 1990. Code Case N-480 provided requirements for both examination and evaluation of pipe subjected to wall thinning. Code Case N-597 of Section XI, *Requirements for Analytical Evaluation of Pipe Wall Thinning* [3], provides improved evaluation procedures and acceptance criteria for Class 1, 2, and 3 piping items subjected to wall thinning mechanism(s) such as flow-accelerated corrosion. This Code Case was first published in 1998, and the current version is Code Case N-597-2. Code Case N-597 supersedes Code Case N-480.

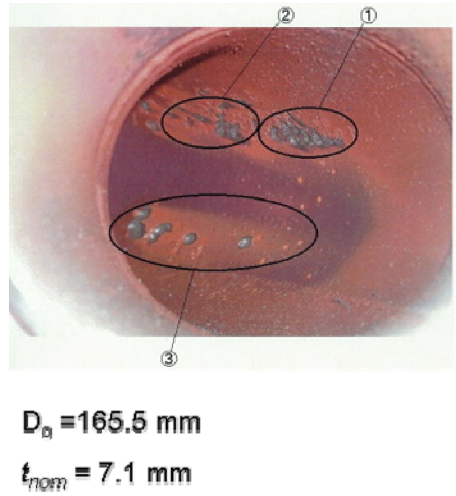

Figure 1: Wall Thinning Caused by Flow-Accelerated Corrosion in a BWR Feed Water Heater Bent Elbow Downstream of an Orifice

Code Case N-597-2 was developed in response to a need for ASME B&PV Code evaluation rules for piping items degraded by the effects of flow-accelerated corrosion and other corrosion mechanisms that result in nonplanar flaws. For example, wall thinning caused by flow-accelerated corrosion in a Boiling Water Reactor (BWR) feedwater heater bent elbow downstream of an orifice is shown in Figure 1. The Code Case provides a clear, technically correct and conservative basis for the evaluation of such a component's fitness for continued service in accordance with the intent of the design Code. Such evaluation is essential to the safe operation of the piping system while acknowledging the reality of aging-related degradation mechanisms and the need to properly plan for component repair or replacement. The Code Case covers evaluation of wall thinning in straight pipe, reducers, elbows, bends, tees and branch connections. The scope of the Code Case is limited to structural integrity evaluation procedures for thinned areas in piping items resulting from various degradation mechanisms such as flow-accelerated corrosion. The Code Case cannot provide generically applicable requirements for prediction of wall thinning rates, or for inspection, since such requirements are specific to a given situation.

The technical basis for Code Case N-597-2 was first published at the *1999 ASME Pressure Vessels and Piping Conference* [4]. The technical basis for a number of the procedures to evaluate wall thickness less than the Construction Code Design Pressure-based minimum allowable wall thickness, t_{min}, were published previously in the *Electric Power Research Institute* (*EPRI*) Report NP-5911SP [5]. Additional description of the technical basis is provided in Reference [6].

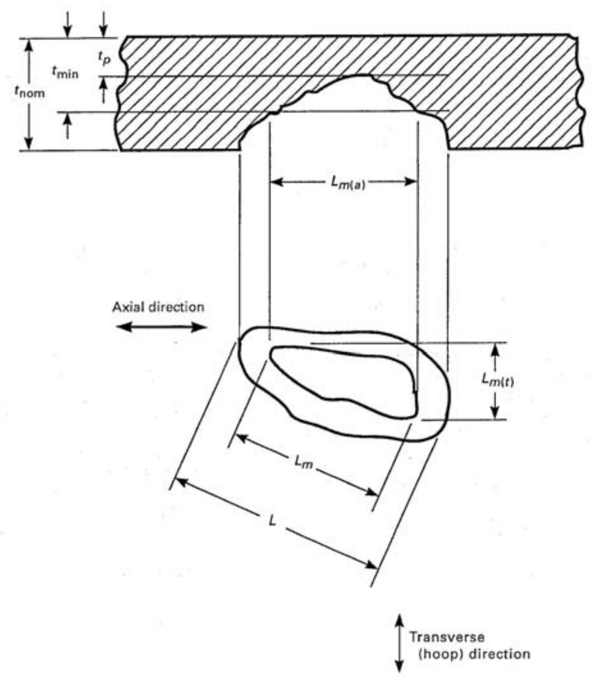

Figure 2: Illustration of Wall Thinning (Figure -3622-2 of Code Case N-597-2)

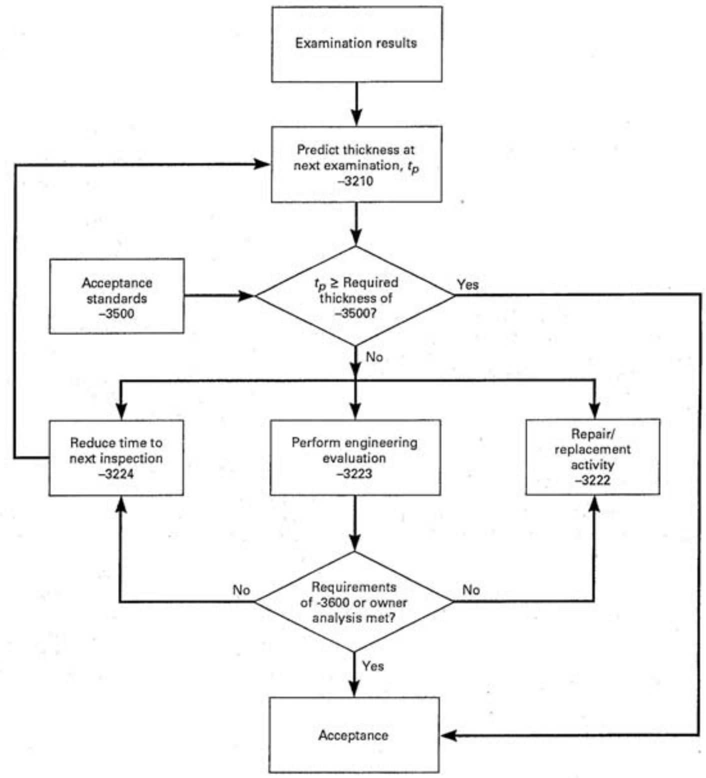

Figure 3: Flowchart of an Evaluation in Accordance with Code Case N-597-2 (Figure -3220-1 of Code Case N-597-2)

Since publication of the 1999 technical basis paper [4], the ASME Section XI Working Group on Pipe Flaw Evaluation has identified the need for an expanded explanation of the technical basis for the Code Case, particularly those procedures for the evaluation of wall thickness less than t_{min}. The paper includes an overview of the Code Case evaluation procedures and acceptance criteria, plus the expanded technical basis addressing analytical evaluation of wall thickness under pressure loading and piping longitudinal stress analysis. Comparison of evaluation procedures and acceptance criteria against experiments, as well as against an actual pipe field failure, is also provided. The paper continues with a discussion section, plans for future development, a summary and conclusions.

PREDICTION OF WALL THICKNESS

Article -3210 of Code Case N-597-2 requires prediction of the distribution of remaining wall thickness at the end of the evaluation period, t_p. The current wall thickness profile is first characterized. The predicted wall thickness at the end of the evaluation period is then determined using the current wall thickness and predicted future wall thinning rate. Wall thinning resulting in a nonplanar flaw is illustrated schematically in Figure 2, wherein the flaw configuration, including predicted wall thickness, is described. With reference to Figure 2, the maximum extent, L_m, of a local thinned area with t_p less than the Construction Code Design Pressure-based minimum allowable wall thickness, exclusive of corrosion allowance, t_{min}, may also change during the evaluation period and this must be taken into account. Methods to predict rate of wall thinning and frequency of inspection of locations of wall thinning are beyond the scope of the Code Case and are the responsibility of the Owner.

WALL THICKNESS ACCEPTANCE STANDARDS

The flowchart in Figure 3 depicts the progression of a Code Case N-597-2 evaluation. At the first level, the Acceptance Standards of Article -3500 of the Code Case are applied. The predicted wall thickness at the end of the evaluation period, t_p, is compared against piping specification tolerances, i.e., the range of thickness at which the piping item is provided by the manufacturer. For straight pipe and elbows purchased to a nominal pipe specification, the allowable wall thickness under-tolerance is 12.5%. Compliance with the Acceptance Standards require that t_p must be not less than $0.875t_{nom}$, where t_{nom} is the nominal wall thickness of the piping item. This first level of screening guards against rejection of piping that may appear to have experienced wall loss; but has actually experienced little or no wear.

The Acceptance Standards require piping items procured to a minimum wall thickness specification to be evaluated against the minimum thickness specified.

When the predicted wall thickness does not satisfy the Acceptance Standards, an engineering evaluation based on analytical procedures may be performed to justify continued operation. Detailed analytical procedures for Class 2 and 3 piping items are provided in the Code Case as described below.

However, there is a lower wall thickness limit below which no further evaluation is permitted. Regardless of the results of the analytical evaluation, Class 1 piping items of predicted remaining wall thickness at the end of the evaluation period, t_p, less than $0.3t_{nom}$ may not be further evaluated by the Code Case. The predicted wall thickness of a Class 2 piping item less than $0.2t_{nom}$ may not be further evaluated under the Code Case. The wall thickness limit of $0.2t_{nom}$ is recommended in the *EPRI* Report NP-5911SP [5]. For Class 1 piping items, the increased wall thickness limit of $0.3t_{nom}$ was specified due to the higher safety significance of a Class 1 piping item. In general, the predicted wall thickness of a Class 3 piping item less than the lesser of $0.2t_{nom}$ or $0.5t_{min}$ may not be further evaluated under the Code Case. A more flexible wall thickness limit for Class 3 piping items has been provided since many lower pressure piping systems may have a t_{min} that is less than $0.2t_{nom}$. For higher pressure piping, when t_{min} approaches t_{nom}, the limit of $0.5t_{min}$ would be significantly larger than $0.2t_{nom}$, and would be overly conservative. The Class 3 wall thickness limit is therefore the lesser of $0.2t_{nom}$ or $0.5t_{min}$. However, a moderate energy Class 3 piping item with maximum operating temperature not exceeding 200°F (93°C) and maximum operating pressure not exceeding 275 psi (1.9 MPa) may be evaluated by alternate methods, including that specified in Code Case N-513-2 [7].

ANALYTICAL EVALUATION PROCEDURES

Analytical evaluation procedures are permitted by Code Case N-597-2 for thinned piping items with remaining wall thickness less than required by the Acceptance Standards described above. The analytical evaluations may be performed using either the Construction Code equations, or the equations in the Code Case. In either case, the loadings, load combinations, and allowable material properties should be from the design analysis of record. Article -3600 describes analytical evaluation procedures for Class 2 and 3 piping items. The analytical evaluation of Class 1 piping items is not prohibited by the Code Case; but, no procedures are provided. The Code Case requires separate evaluation of: (1) wall thickness under pressure loading; and (2) piping longitudinal stresses. The interaction of multiple flaws must be taken into account in the evaluation.

Thinned piping items evaluated under -3600 are subject to monitoring requirements so as to ensure the evaluation of the actively thinning item remains valid or is further evaluated. The frequency and method of monitoring are the responsibility of the Owner.

Wall Thickness Evaluation

Article -3622 of the Code Case requires evaluation of the piping wall thickness to withstand the effects of pressure in accordance with the applicable Construction Code.

Wall Thickness Evaluation Based on t_{min}. Design Pressure, P, is used to calculate minimum allowable uniform wall thickness, exclusive of corrosion allowance, t_{min}, that will maintain hoop stress in the piping item within Code allowable stresses as defined in the applicable piping Construction Code, such as Section III of the ASME B&PV Code [8]. For example, for straight pipe, elbows and bends, the minimum wall thickness is given by [3]

$$t_{min} = \frac{P D_o}{2(S + yP)} \tag{1}$$

where D_o is the outside diameter of the pipe, S is the Code-specified maximum allowable stress, and y is a factor required by the applicable piping Construction Code and is equal to 0.4. A predicted remaining wall thickness t_p no less than $0.9t_{min}$ satisfies the wall thickness evaluation requirements. The basis for accepting 90% of t_{min} is ASME Section III Code Interpretation III-1-83-169 [9], which states that primary stresses in a local area are allowed to exceed the allowable stress limits by 10 percent (the stated 90% is 100%/110% rounded off). Although this Interpretation specifically addresses Class 2 components, the approach is applicable to Class 1 components because it is based on NB-3213.10 of Section III of the ASME B&PV Code. The criterion can be extended to Class 3 components as well, on the basis that Class 3 design rules are essentially identical to Class 2 rules.

Specific requirements are provided in -3622 of the Code Case for the inner bend radius of elbows and bends to account for the higher intrados hoop stress. The technical basis for these requirements is provided in Reference [4].

The Code Case further provides specific requirements for t_{min} in branch connections, tees and reducers. For regions outside the reinforcement areas in branch connections and tees, t_{min} is that of the corresponding pipe. This is supported by Paragraph 104.3 of ANSI/ASME B31.1-1983 [10]. The local thinning evaluations of -3622.2 through -3622.6 are not permitted for regions within the specified reinforcement zone adjacent to any branch connection on the run pipe. For reducers, t_{min} for each end is as calculated for straight pipe of the corresponding size. The t_{min} for the conical portion of the reducer and the transition at the larger end is that of the larger end. The smaller end transition t_{min} varies linearly from that of the small end to that of the conical section. This is a conservative treatment of the diameter effects. The local thinning evaluations of -3622.2 through -3622.6 are not permitted for the small transition of a reducer. Additional details of the technical basis are provided in Reference [4].

Allowable Local Wall Thickness Evaluation. The Code Case provides detailed analysis procedures for the evaluation of localized thinning to a predicted remaining wall thickness, t_p, less than $0.9t_{min}$. The evaluation involves calculation of the minimum allowable local wall thickness of the piping item, t_{aloc}, with

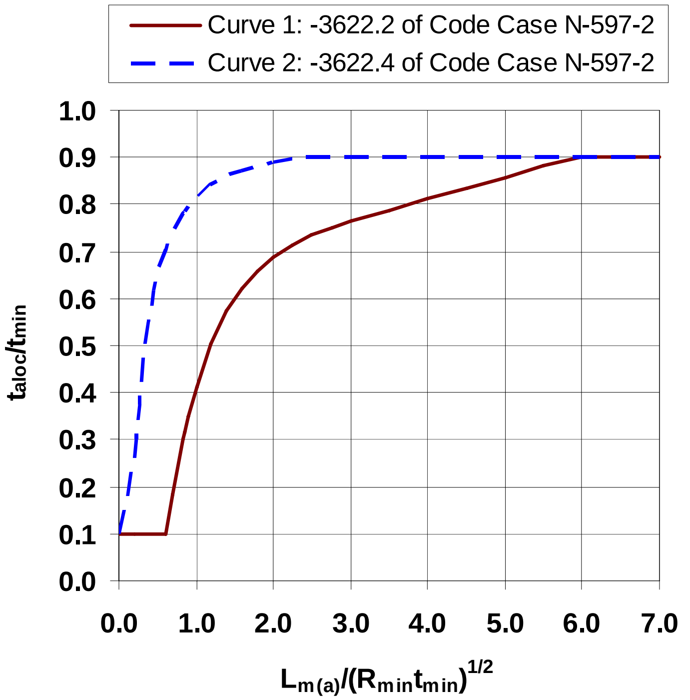

Figure 4: Normalized Allowable Wall Thickness in Thinned Section, t_{aloc}/t_{min}, from Table -3622-1 of Code Case N-597-2

calculations specific to thinning extent: (a) limited transverse (circumferential) extent; (b) limited axial and transverse extent; or (c) unlimited transverse extent.

(a) Article -3622.2 provides a procedure to determine t_{aloc} for limited transverse extent, where the transverse extent, $L_{m(t)}$, of wall thinning predicted to be less than t_{min} does not exceed $(R_{min}t_{min})^{1/2}$. The parameter R_{min} is the mean radius of the piping item based on the nominal outside radius and t_{min}. The ratio of t_{aloc}/t_{min} is given as a function of $L_{m(a)}/(R_{min}t_{min})^{1/2}$ in the first column of Table -3622.1 of the Code Case, and in this paper is given in Table 1 and by Curve 1 of Figure 4. The parameter $L_{m(a)}$ is the axial extent of wall thinning predicted to be less than t_{min}. For straight pipe, when $L_{m(t)}$ is predicted to exceed $(R_{min}t_{min})^{1/2}$, the first column of Table -3622-1 of the Code Case may still be used, but a wall thickness t_b must be added to t_{aloc} from the table, where t_b is the uniform thickness required by the Construction Code to withstand sustained and occasional bending loadings in the absence of internal pressure, thermal expansion and anchor movement loadings. The technical basis for -3622.2 is given in the *EPRI* Report NP-5911SP [5], and summarized in Appendix A of this paper.

(b) Article -3622.3 provides a procedure to determine t_{aloc} for limited axial and transverse extent, where the maximum extent, L_m, of wall thinning predicted to be less than t_{min} does not exceed

Table 1: Table -3622-1 of Code Case N-597-2 that Provides Ratio of t_{aloc}/t_{min} for Limited (-3622.2) and Unlimited (-3622.4) Transverse Extent of Wall Thinning

$L_{m(a)}/(R_{min}t_{min})^{1/2}$	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

$2.65(R_{min}t_{min})^{1/2}$, and t_{nom} is greater than $1.13t_{min}$. Article -3622.3 contains two main requirements:

(i) First, protection against pressure blowout of the local thinned area must be assured by satisfying Eq. (2).

$$\frac{t_{aloc}}{t_{min}} \geq \frac{0.353L_m}{\left(R_{min}\,t_{min}\right)^{1/2}} \quad (2)$$

When L_m is at the applicability limit of $2.65(R_{min}t_{min})^{1/2}$, the value of t_{aloc} is equal to $0.935t_{min}$.

(ii) Second, adequate area reinforcement of the thinned area must be demonstrated by satisfying either Eq. (3),

$$\frac{t_{aloc}}{t_{min}} \geq 1 - 1.5\frac{(R_{min}t_{min})^{1/2}}{L}\left(\frac{t_{nom}}{t_{min}} - 1\right) \quad (3)$$

or by satisfying Eq. (4),

$$\frac{t_{aloc}}{t_{min}} \geq 1 - \frac{0.935A_{rein}}{L_m t_{min}} \quad (4)$$

where A_{rein} is the reinforcement area available in the pipe wall based on the predicted thickness distribution in excess of t_{min} and within the limits of reinforcement of the Construction Code for an opening with diameter L_m. The technical basis for -3622.3 is given in Appendix B of this paper.

(c) Article -3622.4 provides a procedure to determine t_{aloc} for unlimited transverse extent, where $L_{m(t)}$ is predicted to exceed $(R_{min}t_{min})^{1/2}$. The ratio of t_{aloc}/t_{min} is given as a function of $L_{m(a)}/(R_{min}t_{min})^{1/2}$ in the second column of Table -3622-1 of the Code Case, and in this paper is given in Table 1 and by Curve 2 of Figure 4. The technical basis for -3622.4 is given in the *EPRI* Report NP-5911SP [5], and summarized in Appendix A of this paper.

The Code Case provides specific requirements for evaluation of local thinning in elbows, bends, and reducers, with minimum acceptable separation distances specified between adjacent thinned areas.

Piping Stress Evaluation

In addition to a wall thickness evaluation, -3623 of the Code Case requires evaluation of the piping longitudinal stresses in the thinned area in accordance with the applicable Construction Code. These evaluations include longitudinal pressure stresses and longitudinal bending stresses.

Piping Stress Evaluation for Thinned Cross-Sections. Piping stress analysis is typically based on nominal piping thickness, while manufacturing tolerance allows for the actual piping to be installed 12.5% thinner than nominal. To account for this tolerance and avoid the false wall thinning evaluation of an unworn piping item which was installed with minimum thickness $0.875t_{nom}$, allowable stresses used in the stress analysis based on predicted wall thickness t_p may be multiplied by 1/0.875 or 1.143. Allowable stress for the evaluation of piping procured to a minimum wall thickness is unchanged.

Wall thinning also causes changes in the pipe metal area, pipe inside area, section modulus, and stress indices or stress intensification factors. The effects of these changes on piping stresses must be taken into account in the evaluation. Methods for calculation of stresses in a non-uniformly thinned pipe are described in Reference [6]. For example, in a detailed stress analysis based on measured geometry of the thinned area, the nominal longitudinal stress due to internal pressure, S_p, is given by

$$S_p = \frac{P A_i}{A_p} \quad (5)$$

where A_i is the predicted inside area of the cross-section of the pipe, and A_p is the predicted metal cross-sectional area of the pipe.

Wall thinning also changes nominal longitudinal bending stresses. For example, in a detailed stress analysis based on measured geometry of the thinned area, the nominal longitudinal stress due to bending moments, S_b, is given by

$$S_b = \frac{M_b + P A_o \delta}{Z_{min}} \quad (6)$$

where M_b is the applied bending moment from the design analysis, δ is the nominal distance between the center of the pipe and the neutral axis of the thinned pipe section, Z_{min} is the predicted minimum section modulus of the thinned section of pipe, and A_o is the total cross-sectional area of the pipe based on nominal outside diameter, and is given by

$$A_o = \frac{\pi D_o^2}{4} \quad (7)$$

The Code Case contains specific requirements for calculating nominal longitudinal stress in thinned branch connections and reducers. Wall thinning effects on stress indices and stress intensification factors must be taken into account.

Evaluation for Cyclic Loading. Article -3625 of the Code Case does not require thermal expansion and anchor movement stress evaluation of any piping item(s) of predicted minimum wall thickness, $t_{p,min}$, not less than $0.75t_{nom}$ and subject to no more than 150 equivalent full temperature cycles at the time of the next inspection. Piping item(s) designed with consideration of thermal expansion stresses not meeting this requirement are subject to evaluation with revised stress intensification factors or stress indices to be calculated based on remaining wall thickness. Alternatively, modified stress range reduction factors, f, which are given in Table -3625-1 of the Code Case may be used in the evaluation. The modified stress range reduction factors are based on an assumed increase in the stress intensification factor by a factor of 2 over the design life of the piping item. The factor of 2 is considered reasonable considering typical geometries of thinned areas. The technical basis for the exclusion criteria and the development of modified stress range reduction factors is described in Appendix C of this paper. The potential for local overstrain of the thinned area of the pipe must also be considered, with evaluation methods and acceptance criteria specified by the Owner.

COMPARISON OF EVALUATION PROCEDURES AND ACCEPTANCE CRITERIA AGAINST EXPERIMENTS

The *EPRI* report NP-5911SP [5] contains a comparison of the -3622.4 acceptance criteria, in the second column of Table 1, with the results of corroded pipe burst tests performed at Battelle Columbus Laboratories [11]. For each of these tests, the measured

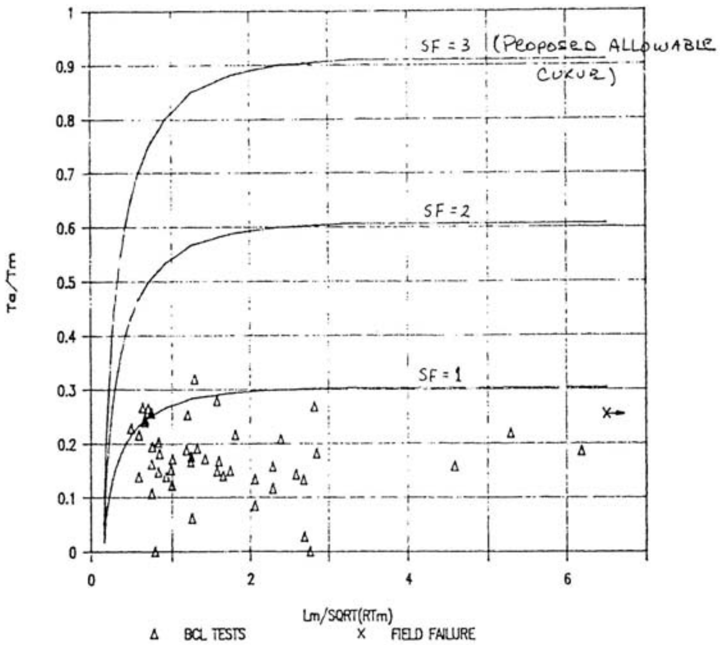

Figure 5: Comparison of Normalized Allowable Wall Thickness in Thinned Section, t_{aloc}/t_{min}, with Test Results and Surry Unit 2 Field Failure (from Reference [5])

wall thickness in the corroded area was divided by the minimum allowable wall thickness, t_{min}, as calculated by Construction Code methods at an estimated Design Pressure. The experimental data is plotted versus $L_{m(a)}/(Rt_{min})^{1/2}$ as triangles in Figure 5, where the label of the ordinate "Ta/Tm" is actually t_{aloc}/t_{min}, R is the pipe mean radius based on the nominal outside radius, and t_{nom} is assumed equal to t_{min}. The -3622.4 acceptance criteria of t_{aloc}/t_{min} versus $L_{m(a)}/(R_{min}t_{min})^{1/2}$ is the curve labeled "SF = 3 (Proposed Allowable Curve)," where 3 is the nominal Code structural (safety) factor for bursting under pressure loading. Curves "SF = 2" and "SF = 1" have been scaled from "SF = 3…". As the majority of the burst test data points lie below the "SF = 1" curve, a nominal structural factor of 3 is implied in the acceptance criteria.

Data from pipe burst test CS-13 performed by JAERI [12] has also been compared against the acceptance criteria of the second column of Table -3622-1 of the Code Case. The burst test was performed at ambient temperature on an STPT 370 carbon steel pipe of nominal wall thickness 0.43 in. (11 mm) machined on the inside diameter to 0.043 in. (1.1 mm) remaining wall thickness. For the purpose of this calculation, the burst pressure of 1,150 psi (7.94 MPa) was assumed to be the Design Pressure. The t_{min} was calculated to be 0.20 in. (5.1 mm). The axial extent, $L_{m(a)}$, of wall thickness less than t_{min} was 5.9 in. (150 mm). The transverse extent, $L_{m(t)}$, of wall thickness less than t_{min} corresponded to 90 degrees, or $5.6(R_{min}t_{min})^{1/2}$, and the procedures of -3622.4 of the Code Case were

Table 2: Comparison of Normalized Allowable Wall Thickness in Thinned Section, t_{aloc}/t_{min}, with a Pipe Burst Test and Surry 2 Field Failure

PARAMETER	BURST TEST CS-13	SURRY-2 FIELD FAILURE
Material	STPT 370	A106B
Temperature – °F (°C)	Ambient	370 (188)
Nominal Pipe Diameter, D_o – in. (mm)	6.5 (165)	18 (457)
Nominal Wall Thickness, t_{nom} – in. (mm)	0.43 (11)	0.50 (13)
Design Pressure, P – psi (MPa)	na	600 (4.14)
Burst Pressure – psi (MPa)	1,150 (7.94)	370 (2.55)
Code Allowable Stress, S – ksi (MPa)	18.1 (125)	15 (103)
Code Minimum Allowable Wall Thickness, t_{min} – in. (mm)	0.20 (5.1)	0.35 (9.0)
Pipe Mean Radius, R_{min}, based on t_{min} – in. (mm)	3.15 (80)	8.82 (224)
Transverse Extent of Thinned Region, $L_{m(t)}$ – in. (mm)	4.43 (112)	na
Axial Extent of Thinned Region, $L_{m(a)}$ – in. (mm)	5.91 (150)	24 (610)
$L_{m(t)}/(R_{min}t_{min})^{1/2}$	5.56	na
$L_{m(a)}/(R_{min}t_{min})^{1/2}$	7.41	13.6
t_{aloc}/t_{min} from Table -3622-1 of Code Case N-597-2	0.90	0.90
Allowable Local Wall Thickness, t_{aloc} – in. (mm)	0.18 (4.6)	0.32 (8.1)
Wall Thickness in Thinned Region – in. (mm)	0.043 (1.1)	0.048 (1.2)

used. A summary of the calculations is provided in Table 2, where t_{aloc}/t_{min} is 0.90, and t_{aloc} is 0.18 in. (4.6 mm). Thus, a Code Case evaluation would have shown the 0.043 in. (1.1 mm) remaining wall thickness to be unacceptable, with a large margin between the acceptable minimum thickness and the thickness at actual failure.

COMPARISON OF EVALUATION PROCEDURES AND ACCEPTANCE CRITERIA AGAINST ACTUAL PIPE FIELD FAILURE

The wall thickness profile [5] of the ruptured Surry Unit 2 A106B carbon steel feedwater pump suction line elbow [13,14] was similarly compared against the -3622.4 acceptance criteria. After 13 years of operation, flow-accelerated corrosion had reduced the initial 0.50 in. (13 mm) nominal wall thickness to 0.048 in. (1.2 mm) at the failure initiation site. The t_{min} was calculated as 0.35 in. (9.0 mm) [5]. The axial extent, $L_{m(a)}$, of wall thickness less than t_{min} was 24 in. (610 mm). The transverse extent, $L_{m(t)}$, of the thinned area below t_{min}

was reasonably assumed to exceed $(R_{min}t_{min})^{1/2}$, and the Code Case -3622.4 evaluation was performed. A summary of the calculations is provided in Table 2, where t_{aloc}/t_{min} is 0.90, and t_{aloc} is 0.32 in. (8.1 mm). Based on comparing t_{aloc} with the wall thickness at the failure location of 0.048 in. (1.2 mm), the wall thinning in Surry Unit 2 would have clearly been unacceptable using the acceptance criteria in the Code Case.

DISCUSSION

Margins Against Failure Implicit in Acceptance Criteria

Calculations described in the 1999 technical basis document [4] demonstrate that Code Case N-597-2 acceptance criteria are no less conservative than that of the limit load based pipe flaw evaluation procedures defined in Section XI of the ASME B&PV Code [1]. The Code Case N-597-2 technical basis described in this paper and in References [4,5] including the evaluation of local thinning less than t_{min}, demonstrate compliance with ASME B&PV Code design-intent margins. The acceptance criteria have also been validated by pipe burst experiments described above.

Prediction of Rate of Wall Thinning and Monitoring Frequency

The scope of Code Case N-597-2 is intentionally limited to the structural integrity evaluation of piping items with wall thickness not meeting Acceptance Standards. The Code Case cannot specify generically applicable wall-thinning prediction procedures nor inspection requirements, since such requirements are specific to a given situation. However, the Code Case provisions do require periodic monitoring of any piping item evaluated under its analytical procedures. Each U.S. nuclear plant maintains a formal, comprehensive program dedicated to the prediction, monitoring and mitigation of flow-accelerated corrosion-related degradation of piping and other pressure boundary items. The long-term conduct of the program is an Owner commitment under the requirements of NRC Bulletin 87-01 [15].

Most, if not all, U.S. nuclear plant flow-accelerated corrosion programs are structured as recommended in the *EPRI Nuclear Safety Analysis Center* (*NSAC*) Report 202L-R2 [16]. The guidelines contained in *NSAC*-202L were developed with extensive industry involvement in the years following the Surry Unit 2 event of December 1986 [13,14]. The guidelines describe proven techniques for the determination of flow-accelerated corrosion susceptibility, wall thinning rate prediction and monitoring. A well-attended Users Group provides the forum for the continual sharing of experience and development of expertise among the international community of flow-accelerated corrosion engineers.

Applicability to Class 1 Piping Items

Historically, wall thinning degradation has been much less frequent in Class 1 piping systems as compared with Class 2 and 3, and higher priority was given to development of evaluation procedures and acceptance criteria for wall thinning in Class 2 and 3 piping items. Engineering evaluation procedures and acceptance criteria for wall thinning in Class 1 piping items are not specified in Code Case N-597-2. Efforts are now underway in the ASME Section XI Working Group on Pipe Flaw Evaluation to develop evaluation procedures and acceptance criteria for wall thinning in Class 1 piping items.

Applicability to Wall Loss Other Than Flow-Accelerated Corrosion

Code Case N-597-2 evaluation procedures and acceptance criteria are applicable to wall thinning caused by corrosion phenomenon other than flow-accelerated corrosion, including Microbiologically-Induced Corrosion (MIC) and pitting. As is the case with flow-accelerated corrosion, the prediction of wall loss is outside the scope of the Code Case. However, significant industry experience with these mechanisms indicates the onset of damage occurring with failure of some mitigating measure, such as the exhaustion of a biocide. In such a case, the degradation process is likely to be arrested following discovery; leaving the evaluation limited to the existing damage. In this situation the Code Case may provide significant benefit.

FUTURE DEVELOPMENTS

A proposed implementation of Code Case N-597-2 as a nonmandatory Appendix to Section XI of the ASME B&PV Code is under development by the ASME Section XI Working Group on Pipe Flaw Evaluation. The evaluation procedures and acceptance criteria for wall thinning in Class 1 piping items that are under development are expected to be included in the nonmandatory Appendix. The proposed nonmandatory Appendix would then provide evaluation procedures and acceptance criteria for wall thinning in Class 1, 2 and 3 piping items.

SUMMARY AND CONCLUSIONS

(a) Code Case N-597-2 of Section XI of the ASME B&PV Code provides structural integrity evaluation procedures and acceptance criteria for wall thinning in piping systems, such as that caused by flow-accelerated corrosion. The acceptance criteria in the Code Case maintain ASME B&PV Code design-intent margins.

(b) The Code Case does not provide requirements for reduction of wall-thinning rate, nor for inspection.

(c) The comparison of Code Case evaluations against results of pipe burst experiments demonstrated the conservatism of the Code Case evaluation procedures and acceptance criteria. The Surry Unit 2 feedwater pump suction elbow that ruptured in 1986 would have been found unacceptable under the Code Case.

(d) A nonmandatory Appendix to Section XI providing evaluation procedures and acceptance criteria for wall thinning in Class 1, 2 and 3 piping items is under development.

ACKNOWLEDGEMENTS

Code Case N-597-2 was developed by the Section XI Task Group on Erosion/Corrosion Acceptance Criteria, and has subsequently been updated by the Section XI Working Group on

Pipe Flaw Evaluation. The authors wish to acknowledge the contributions of the many individuals who were, and still are, involved with these ASME Code activities. One of the original authors of the Code Case, Art Deardorff, is acknowledged for his valuable comments on this paper. Valuable assistance provided by Russ Cipolla and Keith Wichman is also appreciated.

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APPENDIX A

TECHNICAL BASIS FOR ALLOWABLE LOCAL WALL THICKNESS FOR LIMITED AND UNLIMITED TRANSVERSE EXTENT

The technical basis for Code Case N-597-2 evaluation procedures for allowable local wall thickness for limited (-3622.2) and unlimited (-3622.4) transverse extent of wall thinning is summarized in this Appendix.

ALLOWABLE LOCAL WALL THICKNESS FOR LIMITED TRANSVERSE EXTENT

ANSI/ASME B31.G Acceptance Criteria

The technical basis for the allowable local wall thickness of -3622.2 in the first column of Table -3622-1 of Code Case N-597-2 (Table 1 of this paper), and given by Curve 1 in Figure 4, is from ANSI/ASME B31.G [17,18]. This Standard was developed to assess slot-like axial degradation typical of the lower quadrant of corroded pipelines. Application of ANSI/ASME B31G is limited to carbon and low alloy steels, flaws with relatively smooth contours and with an axial orientation. The acceptance criteria in ANSI/ASME B31G are based on ensuring structural integrity of a pipe under internal pressure without restrictions on transverse extent of the flaw or thinned area. The pipe rupture experiments that were used to develop the acceptance criteria in ANSI/ASME B31G included tests on pipes with full circumference corrosion [5]. The acceptance criteria in ANSI/ASME B31G are given by the following equation for the maximum allowable length of an axial flaw, L_{ax}, as a function of flaw depth.

$$L_{ax} = 1.12\, B\left(D_o t_{nom}\right)^{1/2} \qquad \text{(A-1)}$$

where D_o is the nominal outside diameter of the pipe, t_{nom} is the nominal wall thickness in the region surrounding the axial flaw, and B is given by

$$B = \left[\left(\frac{a/t_{nom}}{1.1(a/t_{nom}) - 0.15}\right)^2 - 1\right]^{1/2} \qquad \text{(A-2)}$$

where a is the axial flaw depth. The value of B may not exceed 4.

From Reference [5], when t_{nom} is equal to the Construction Code Design Pressure-based minimum allowable wall thickness, exclusive of corrosion allowance, t_{min}, the structural (safety) factor against pipe failure in the ANSI/ASME B31G acceptance criteria is 2.7. This structural factor is the same as the structural (safety) factor of 2.7 that is required in Appendix C of Section XI of the ASME B&PV Code [1] for an axial flaw under ASME Service Level A loading. When t_{nom} exceeds t_{min}, the structural factor in the ANSI/ASME B31G acceptance criteria is larger. In Reference [4] it was demonstrated that the ANSI/ASME B31G acceptance criteria provide similar margins to the pipe flaw evaluation rules in Section XI. When the acceptance criteria were implemented into Code Case N-597-2, an upper limit of $0.9t_{min}$ was placed on t_{aloc}. The basis for this upper limit is ASME Section III Code Interpretation III-1-83-169 [9].

Consideration of Bending Stresses

The ANSI/ASME B31.G acceptance criteria define the amount of wall thickness required to sustain pressure loading. However, nuclear piping is subjected to significant bending stresses. To ensure adequate margin against pipe failure in the presence of bending, the applicability of using the ANSI/ASME B31G acceptance criteria in Code Case N-597-2, without additional requirements, is limited to a transverse extent not exceeding $(R_{min}t_{min})^{1/2}$. The parameter R_{min} is the pipe mean radius based on the nominal outside radius and a wall thickness of t_{min}. It was judged in Reference [5] that for transverse extent of wall thinning not exceeding $(R_{min}t_{min})^{1/2}$, adequate margin would still be maintained considering longitudinal stress due to bending moments. Alternatively, for straight pipe, when the transverse extent, $L_{m(t)}$, of wall thinning predicted to be less than t_{min} exceeds $(R_{min}t_{min})^{1/2}$, the first column of Table -3622-1 of the Code Case may still be used, but a wall thickness t_b must be added to t_{aloc} from the table. The wall thickness t_b is the uniform thickness required by the Construction Code to withstand sustained and occasional bending loadings in the absence of internal pressure, thermal expansion and anchor movement loadings. In addition to wall thickness evaluation, -3623 of the Code Case requires evaluation of the piping longitudinal stresses at the cross-section in accordance with the applicable piping Construction Code or by consideration of the actual thickness distribution at the thinned section.

ALLOWABLE LOCAL WALL THICKNESS FOR UNLIMITED TRANSVERSE EXTENT

The technical basis for the allowable local wall thickness of -3622.4 and the second column of Table -3622-1 of Code Case

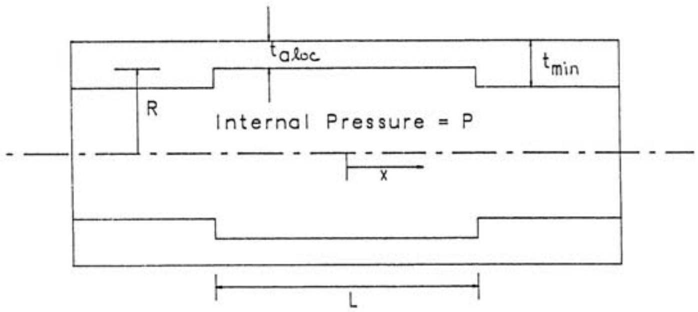

Figure A-1: Idealized Pipe with Thinned Section (from Reference [5])

N-597-2 (Table 1 of this paper), and given by Curve 2 in Figure 4, is described in detail in Appendix A of Reference [5]. A summary is provided below. The analysis is based on evaluations of local membrane stress for a 100 percent of circumference uniformly thinned section in a cylinder with thickness beyond the thinned area equal to t_{min}. The geometry was modeled as an infinitely long pipe with mean radius R and wall thickness t_{min}, and which contains a locally thinned area of length L and wall thickness t_{aloc}, as illustrated in Figure A-1. The pipe is under internal pressure P. The analysis results are conservative for a pipe with nominal wall thickness greater than t_{min}.

Hoop Stress Distribution from Thin-Shell Equations

Axisymmetric, thin-shell equations were used to calculate the membrane hoop stress distribution due to internal pressure in the locally thinned section of the pipe. Details are given in Appendix A of Reference [5]. The development of the equation for membrane hoop stress included the boundary conditions that enforce continuity of radial displacement and slope across the interface between the thinned area and the nominal pipe thickness. Finite element analyses of the same pipe geometry and pressure loading were also performed using thin-shell finite elements. The analytical thin-shell results were in reasonable agreement with the finite element results.

Calculation of t_{aloc}/t_{min} Versus $L_{m(a)}/(R_{min}t_{min})^{1/2}$

NB-3213.10 of Section III of the ASME B&PV Code [8] requires that the length over which the local primary membrane stress exceeds $1.1S_m$ must not exceed $(R_{min}t_{min})^{1/2}$, where S_m is the design stress intensity for an ASME Class 1 component and is given in Part D of Section II of the ASME B&PV Code [19]. In addition, NB-3221.3 of Section III requires that the maximum local primary membrane stress does not exceed $1.5S_m$. As described in Reference [5], iterative calculations were performed to determine, for a given ratio t_{aloc}/t_{min}, the normalized length of the thinned section, $L_{m(a)}/(R_{min}t_{min})^{1/2}$, that would satisfy the NB-3213.10 and NB-3221.3 requirements. The variation of normalized hoop stress divided by S_m versus normalized distance $x/(R_{min}t_{min})^{1/2}$ for $t_{aloc}/t_{min} = 0.5$ is shown in Figure A-2, which was taken from Reference [5]. Determination of the allowable $L_{m(a)}/(R_{min}t_{min})^{1/2}$ for $t_{aloc}/t_{min} = 0.5$ is also illustrated

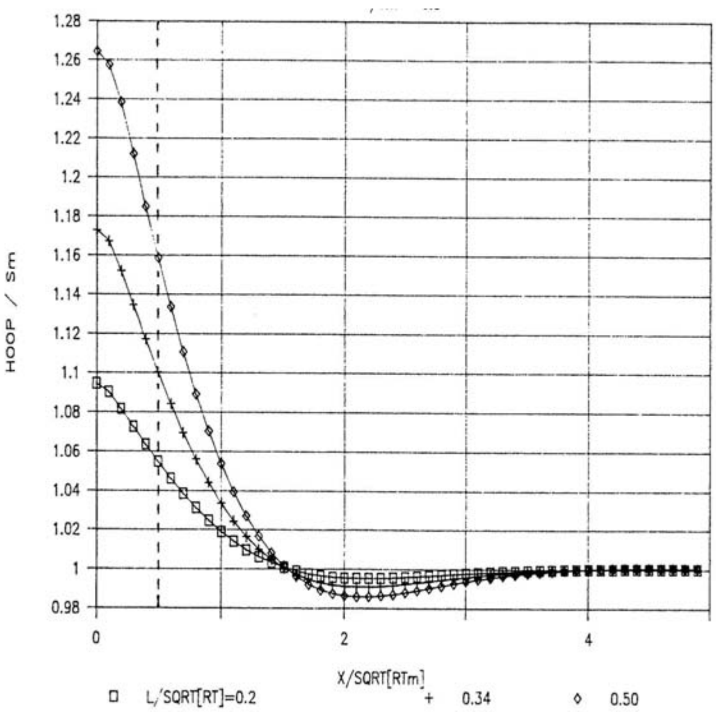

Figure A-2: Illustration of Procedure for Determining Allowable $L_{m(a)}/(R_{min}t_{min})^{1/2}$ of Thinned Section of Pipe for t_{aloc}/t_{min} = 0.5 (from Reference [5])

in this Figure. The iterative procedure was repeated for a range of values of t_{aloc}/t_{min}. The variation of the normalized allowable wall thickness in the thinned section, t_{aloc}/t_{min}, with the normalized length of the thinned section, $L_{m(a)}/(R_{min}t_{min})^{1/2}$, is shown as Curve 2 in Figure 4. When the acceptance criteria were implemented into Code Case N-597-2, an upper limit of $0.9t_{min}$ was placed on t_{aloc}. The basis for this upper limit is ASME Section III Code Interpretation III-1-83-169 [9].

APPENDIX B

TECHNICAL BASIS FOR ALLOWABLE LOCAL WALL THICKNESS FOR LIMITED AXIAL AND TRANSVERSE EXTENT

The technical basis for the Code Case N-597-2 evaluation procedure of -3622.3 for allowable local wall thickness for limited axial and transverse extent of wall thinning is provided in this Appendix.

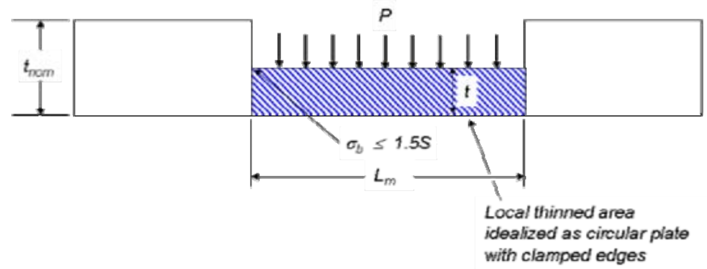

Figure B-1: Local Thinned Region Idealized as a Circular Plate with Diameter L_m and Uniform Thickness

PROTECTION AGAINST PRESSURE BLOWOUT

The local thinned area is idealized as a circular plate with diameter, L_m, and uniform thickness, t, as illustrated in Figure B-1. The dimension L_m is the maximum extent of a local thinned area with predicted wall thickness, t_p, less than the Construction Code Design Pressure-based minimum allowable wall thickness, exclusive of corrosion allowance, t_{min}. The plate is subjected to pressure loading on one side that is equal to the Design Pressure, P. The edges of the plate are clamped and therefore restrained against rotation. From Table 24 of Reference [20], the maximum bending moment, M_b, in the plate due to pressure loading is at the edge of the plate, and is given by

$$M_b = \frac{P}{8}\left(\frac{L_m}{2}\right)^2 \qquad \text{(B-1)}$$

and the corresponding maximum bending stress, σ_b, is given by

$$\sigma_b = \frac{6M_b}{t^2} \qquad \text{(B-2)}$$

Substitution of Eq. (B-1) into (B-2) gives

$$\sigma_b = \frac{3}{16}P\left(\frac{L_m}{t}\right)^2 \qquad \text{(B-3)}$$

From NC-3217(d) of Section III of the ASME B&PV Code [8], the limit on primary membrane plus bending stress for Design conditions is $1.5S$, where S is the allowable stress given in Part D of Section II of the ASME B&PV Code [19]. Substituting this stress limit on σ_b into Eq. (B-3) and rearranging gives a relation for the minimum allowable local wall thickness, t_{aloc}.

$$(t_{aloc})^2 = \frac{1}{8}\frac{P}{S}(L_m)^2 \qquad \text{(B-4)}$$

From NC-3641.1 of Section III of the ASME B&PV Code, the minimum wall thickness required for pressure loading, exclusive of corrosion allowance, t_{min}, is taken to limit the hoop stress to the maximum allowable stress, S.

$$S = P\frac{R_{min}}{t_{min}} \qquad \text{(B-5)}$$

where R_{min} is the mean radius of the piping item based on the nominal outside radius and t_{min}. Substitution of Eq. (B-5) into (B-4) gives

$$(t_{aloc})^2 = \frac{1}{8}\frac{t_{min}}{R_{min}}(L_m)^2 \qquad \text{(B-6)}$$

Dividing both sides of Eq. (B-6) by $(t_{min})^2$ and taking the square root gives the relation for t_{aloc}.

$$\frac{t_{aloc}}{t_{min}} = \frac{0.353L_m}{(R_{min}\,t_{min})^{1/2}} \qquad \text{(B-7)}$$

AREA REINFORCEMENT

Based on Requirements for Class 1 Piping in NB-3643.3

Requirements for reinforcement of openings in Class 1 piping items in NB-3643.3 of Section III of the ASME B&PV Code were adapted to develop an equation to limit the allowable local wall thickness to satisfy the area reinforcement requirements. From NB-3643.3(b)(2), the total cross-sectional area A of reinforcement required for a pipe under internal pressure is

$$A = d\,t_{min} \qquad \text{(B-8)}$$

where d is the diameter of the opening, and t_{min} is the ASME B&PV Code Section III Design Pressure-based minimum allowable wall thickness of the run pipe, exclusive of corrosion allowance. The area required for reinforcement therefore corresponds to the amount of material removed from the pipe to form the opening at a wall thickness of t_{min}, regardless of the nominal wall thickness of the pipe. The same approach was applied to limit the allowable local wall thickness to satisfy the area reinforcement requirements.

With reference to Figure B-2, it was conservatively assumed that the extent, L_m, of the area with wall thickness less than t_{min} is equal to the entire extent, L, of the area with wall thickness less than the nominal wall thickness, t_{nom}. The result is a larger area required for reinforcement compared with using L_m.

$$A = (t_{min} - t_{aloc})L \qquad \text{(B-9)}$$

The requirements of NB-3643.3(c) for limits of reinforcement are satisfied when two-thirds of the required reinforcement is provided within the distance L_A, where

$$L_A = \frac{L}{2} + 0.5(R\,t_{nom})^{1/2} \qquad \text{(B-10)}$$

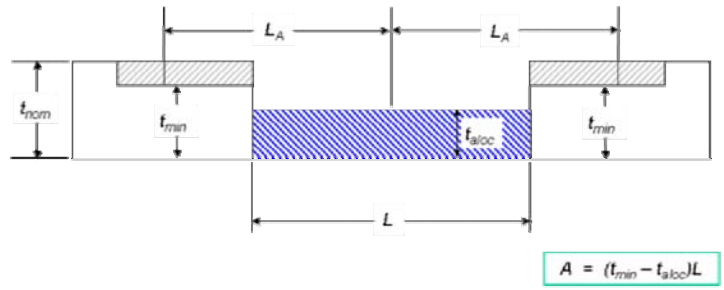

Figure B-2: Illustration of Application of Area Reinforcement Rule from NB-3643.3 of Section III of ASME B&PV Code to Local Thinned Region with Diameter *L* and Uniform Thickness t_{aloc}

and R is the mean radius of the piping item based on nominal outside radius and nominal wall thickness, t_{nom}. Substitution of t_{min} for t_{nom}, and the mean radius of the piping item, R_{min}, based on nominal outside radius and t_{min} for R, gives the more conservative requirement

$$L_A = \frac{L}{2} + 0.5(R_{min}\,t_{min})^{1/2} \qquad \text{(B-11)}$$

With reference to Figure B-2, by requiring that two-thirds of A from Eq. (B-9) lies within the distance L_A given by Eq. (B-11), and that the reinforcement area is available in the pipe wall based on the predicted thickness in excess of t_{min},

$$\frac{2}{3}(t_{min} - t_{aloc})L = (R_{min}\,t_{min})^{1/2}(t_{nom} - t_{min}) \qquad \text{(B-12)}$$

Dividing both sides of Eq. (B-12) by $(2/3)t_{min}L$ and rearranging, one has

$$1 - \frac{t_{aloc}}{t_{min}} = 1.5\frac{(R_{min}\,t_{min})^{1/2}}{L}\left(\frac{t_{nom}}{t_{min}} - 1\right) \qquad \text{(B-13)}$$

Or,

$$\frac{t_{aloc}}{t_{min}} = 1 - 1.5\frac{(R_{min}\,t_{min})^{1/2}}{L}\left(\frac{t_{nom}}{t_{min}} - 1\right) \qquad \text{(B-14)}$$

In Section 6 of the *EPRI* Report NP-5911SP [5], a similar equation for t_{aloc}/t_{min} based on area reinforcement requirements was developed. However, the value of L_m was not assumed to be equal to entire extent, L, of wall thinning. The result is a different equation for t_{aloc}/t_{min} in Reference [5].

Based on Requirements for Class 2 Piping in NC-3643.3

Requirements for reinforcement of openings in Class 2 piping items in NC-3643.3 of Section III of the ASME B&PV Code were also adapted to develop an equation to limit the allowable local wall thickness to satisfy the area reinforcement requirements. From NC-3643.3(c)(3), the total cross-sectional area of reinforcement, A_{rein}, required for a pipe under internal pressure is

$$A_{rein} = 1.07 d\, t_{min} \tag{B-15}$$

The same approach was applied to limit the allowable local wall thickness to satisfy the area reinforcement requirements.

With reference to Figure B-3, and assuming that available reinforcement is beyond the extent, L_m, of the area with wall thickness less than t_{min}, one has

$$A_{rein} = 1.07\left(t_{min} - t_{aloc}\right)L_m \tag{B-16}$$

where A_{rein} is taken to be the reinforcement area available in the pipe wall based on the predicted thickness distribution in excess of t_{min} and within the limits of reinforcement of the Construction Code for an opening with diameter L_m. Dividing both sides of Eq. (B-16) by $1.07L_m t_{min}$ and rearranging, one has

$$\frac{A_{rein}}{1.07\, L_m t_{min}} = \left(1 - \frac{t_{aloc}}{t_{min}}\right) \tag{B-17}$$

Or,

$$\frac{t_{aloc}}{t_{min}} = 1 - \frac{0.935 A_{rein}}{L_m t_{min}} \tag{B-18}$$

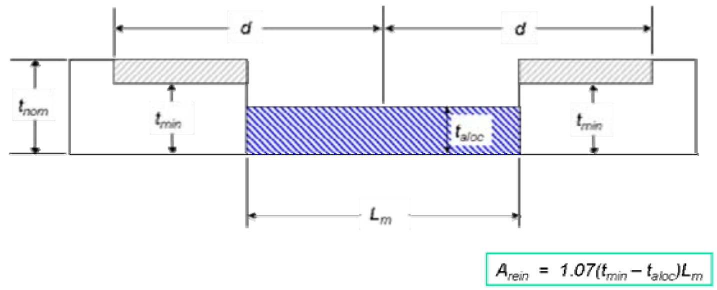

Figure B-3: Illustration of Application of Area Reinforcement Rule from NC-3643.3 of Section III of ASME B&PV Code to Local Thinned Region with Diameter L_m and Uniform Thickness t_{aloc}

APPENDIX C

TECHNICAL BASIS FOR CODE CASE PROCEDURES AND CRITERIA FOR EVALUATION OF CYCLIC LOADING

The technical basis for Code Case N-597-2 procedures and criteria of -3625 for evaluation of cyclic loading is provided in this Appendix. The technical basis is developed using the rules for evaluation of cyclic loading of Class 2 piping in NC-3600 of Section III of the ASME B&PV Code [8]. However, the rules for evaluation of cyclic loading of Class 3 piping in ND-3600 of Section III are essentially the same as for Class 2, and the developments in this Appendix are applicable to both Class 2 and 3 piping.

DERIVATION OF MODIFIED STRESS RANGE REDUCTION FACTORS

Review of Calculation of Stress Range Reduction Factors in Section III of ASME B&PV Code

In NC-3611.2(e) of Section III of the ASME B&PV Code [8], the allowable stress range for expansion stresses for Class 2 piping, S_A, is given by

$$S_A = f\left(1.25 S_c + 0.25 S_h\right) \tag{C-1}$$

where f is the stress range reduction factor for cyclic conditions, S_c is the basic material allowable stress at minimum (cold) temperature, and S_h is the basic material allowable stress at maximum (hot) temperature. The stress range reduction factors are given as a function of number of load cycles in Table NC-3611.2(e)-1 of Section III, and these are reproduced in this Appendix in Table C-1.

The relation between the stress range reduction factor and the allowable number of load cycles follows the fatigue S-N curve from Markl [21], which is given by

$$N = \int_0^N dn = \left(\frac{245{,}000}{i\, s}\right)^5 \tag{C-2}$$

where N is the number of allowable load cycles, n is number of load cycles, i is the stress intensification factor and s is the stress range. By taking the denominator of Eq. (C-2) to scale with the stress range reduction factor, one has

$$N = \left(\frac{245{,}000}{f\, i\, s}\right)^5 \tag{C-3}$$

From Table C-1, for f = 1, the maximum allowable number of load cycles, N, is 7,000, and in this case Eq. (C-3) is written as

$$7{,}000 = \left(\frac{245{,}000}{i\, s}\right)^5 \tag{C-4}$$

Dividing Eq. (C-3) by (C-4) and rearranging, gives the allowable number of load cycles for f less than 1.0,

$$N_0 = \frac{7{,}000}{f^5} \tag{C-5}$$

Table C-1: Modified Stress Range Reduction Factors

N from Table NC-3611.2(e)-1 of Section III of ASME B&PV Code	f from Table NC-3611.2(e)-1 of Section III of ASME B&PV Code	N_0 from Eq. (C-5)	$N' = 0.09524N_0$	N in Table -3625-1 of Code Case N-597-2
7,000 and less	1.0	7,000 and less	667 and less	650 and less
7,000 to 14,000	0.9	7,000 to 11,855	667 to 1,129	650 to 1,100
14,000 to 22,000	0.8	11,855 to 21,362	1,129 to 2,035	1,100 to 2,000
22,000 to 45,000	0.7	21,362 to 41,649	2,035 to 3,967	2,000 to 3,900
45,000 to 100,000	0.6	41,649 to 90,021	3,967 to 8,574	3,900 to 8,500
100,000 and greater	0.5	90,021 to 224,000	8,574 to 21,334	8,500 to 21,000
na	0.4	224,000 to 683,594	21,334 to 65,105	21,000 and greater

where the notation N_0 is used to signify the allowable number of load cycles as calculated using Eq. (C-5) based on the as-installed geometry of the piping item.

Values of N_0 were calculated for f equal to 0.4 through 0.9, and are compared in Table C-1 with the similar values from Table NC-3611.2(e)-1 of Section III of the ASME B&PV Code. The values of N_0 calculated from Eq. (C-5) are in reasonable agreement with the rounded values from Table NC-3611.2(e)-1 of Section III.

Calculation of Modified Stress Range Reduction Factors

The number of allowable load cycles corresponds to a cumulative fatigue usage factor of 1.0.

$$\int_0^N \frac{dn}{N} = 1.0 \tag{C-6}$$

Substituting Eq. (C-2) for N into Eq. (C-6) gives

$$\int_0^N \left(\frac{i s}{245{,}000}\right)^5 dn = 1.0 \tag{C-7}$$

For a stress intensification factor that does not remain constant over the life of the piping item, and a constant stress range,

$$\int_0^N i^5 dn = \left(\frac{245{,}000}{s}\right)^5 \tag{C-8}$$

It is assumed that there is a linear increase in i from the initial value i_0 over a shortened life N',

$$i = \left(1 + \frac{k\,n}{N'}\right) i_0 \tag{C-9}$$

where k is a constant. Equation (C-9) is written in differential form as

$$di = \frac{k\,i_0}{N'} dn \tag{C-10}$$

Or,

$$dn = \frac{N'}{k\,i_0} di \tag{C-11}$$

The variable of integration is changed from n to i by substituting Eq. (C-11) into (C-8),

$$\int_{i_0}^{i_0(1+k)} \frac{N'}{k\,i_0} i^5 di = \left(\frac{245{,}000}{s}\right)^5 \tag{C-12}$$

Integrating Eq. (C-12) and solving for N' gives

$$N' = \frac{6\,k}{(1+k)^6 - 1}\left(\frac{245{,}000}{i_0\,s}\right)^5 \tag{C-13}$$

Or,

$$N' = \frac{6\,k}{(1+k)^6 - 1} N_0 \tag{C-14}$$

where N_0 is the allowable number of load cycles based on the design-basis dimensions of the piping item.

$$N_0 = \left(\frac{245{,}000}{i_0\,s}\right)^5 \tag{C-15}$$

It is assumed that i increases by a factor of 2 due to wall thinning over the life of the piping item. In this case $k = 1$, and

$$N' = \frac{6}{2^6 - 1} N_0 \tag{C-16}$$

Or,

$$N' = 0.09524 N_0 \quad \text{(C-17)}$$

Values of N_0 that are given in Table C-1 were substituted into Eq. (C-17), and the resultant values of N' are given in Table C-1. The calculated values of N' were then rounded down, and the rounded values are given as N in the last column of Table C-1. These values of N are also given in Table -3625-1 of Code Case N-597-2.

DERIVATION OF CYCLIC EVALUATION EXCLUSION CRITERIA

Allowable Number of Load Cycles in Cyclic Evaluation Exclusion Criteria

From NC-3611.2(e) of Section III of the ASME B&PV Code, the allowable stress range for expansion stresses for Class 2 piping, S_A, is given by Eq. (C-1). The fatigue S-N curve from Markl is given by [21]

$$N = \left(\frac{245{,}000}{i\,s} \right)^5 \quad \text{(C-18)}$$

It is assumed that the pipe has been designed to the maximum allowable stress range for expansion stresses, which corresponds to a stress range reduction factor, f, equal to 1.0, and a maximum allowable number of load cycles, N, equal to 7,000. In this case, Eq. (C-18) is written as

$$7{,}000 = \left(\frac{245{,}000}{i\,s} \right)^5 \quad \text{(C-19)}$$

Equation (C-19) is re-arranged to give the maximum allowable stress amplitude for 7,000 load cycles or less.

$$i\,s = \frac{245{,}000}{7{,}000^{0.2}} = 41{,}701\ psi \quad (288\ MPa) \quad \text{(C-20)}$$

The number of allowable load cycles corresponds to a cumulative fatigue usage factor of 1.0, as given by Eq. (C-6). Substitution of Eq. (C-18) into (C-6) gives

$$\int_0^N (i\,s)^5\, dn = (245{,}000)^5 \quad \text{(C-21)}$$

It is assumed that there is a linear increase in stress intensification factor, i, from the initial value, i_0, based on the design geometry of the piping item to $2i_0$ at the end of life.

$$i = \left(1 + \frac{n}{N} \right) i_0 \quad \text{(C-22)}$$

For a reduction in wall thickness of 25%, down to $0.75t_{nom}$, it is assumed that there is a linear increase of 33% in stress range to the end of life,

$$s = \left(1 + \frac{n}{3N} \right) s_0 \quad \text{(C-23)}$$

where s_0 is the stress range due to cyclic loading based on the design geometry of the piping item. Substitution of Eqs. (C-22) and (C-23) into (C-21) gives

$$\int_0^N \left(1 + \frac{n}{N} \right)^5 \left(1 + \frac{n}{3N} \right)^5 dn = \left(\frac{245{,}000}{i_0 s_0} \right)^5 = 7{,}000 \quad \text{(C-24)}$$

Integrating Eq. (C-24) gives

$$N = 217 \quad \text{(C-25)}$$

This result was conservatively reduced to 150 cycles for the exclusion criteria.

Assessment of Potential for Plastic Ratcheting

Plastic ratcheting is an incremental build-up of plastic strain due to cyclic loads, and may lead to failure of the component. Elastic shakedown occurs when the cyclic strains revert to elastic strains, even when the component had initially yielded. When the cyclic stress range is less than twice the yield strength for the material, elastic shakedown of the component will occur, and plastic ratcheting is not a concern.

From NC-3653.2(c) of Section III of the ASME B&PV Code, the sustained plus expansion stress range, S_{TE}, is limited by

$$S_{TE} \le S_A + S_h \quad \text{(C-26)}$$

where S_A is given by Eq. (C-1). From Part D of Section II of the ASME B&PV Code [19], for typical ferritic nuclear grade piping, S_c is approximately equal to S_h. From Eq. (C-1), S_A is therefore approximately equal to $1.5S_h$. Substitution of $S_A = 1.5S_h$ into Eq. (C-26) gives

$$S_{TE} \le 2.5 S_h \quad \text{(C-27)}$$

From Part D of Section II, the typical Code-specified yield strength of SA-106B or similar piping is 35 ksi (241 MPa) at room temperature, and 28 ksi (193 MPa) at 550°F (288°C). The basic allowable stresses S_c and S_h are both nominally 17 ksi (117 MPa). From Eq. (C-27), the corresponding maximum allowable sustained plus expansion stress range is 42.5 ksi (293 MPa). For a reduction in wall thickness of 25%, down to $0.75t_{nom}$, it is assumed that there is an increase of 33% in stress range. For SA-106B or similar piping designed to the maximum allowable sustained plus expansion stress range of 42.5 ksi (293 MPa), the resultant sustained plus expansion stress range in the thinned area is 56.7 ksi (391 MPa). Since this stress range is not more than twice the yield strength, plastic ratcheting will not occur.