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Pressure Blow Out Assessment for Class 1 Piping with Local Wall Thinning

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ABSTRACT

Wall thinning caused by the flow of water in power piping systems became a major concern to the nuclear power industries. ASME Code Case N-597-3, “Requirements for Analytical Evaluation of Pipe Wall Thinning,” provides procedures and criteria for Code Class 2 and 3 piping for the evaluation of wall thinning. However, analytical evaluation procedure for Class 1 piping is not provideed in the Code Case. Recent full-scale experiments on locally thinned pipes have supported the development of more contemporary failure strength evaluation methodology for Class 1 piping. These evaluation methodologies are applicable for the loading type of bending, tensile or cyclic bending load. Prior to the failure by bending moment, tensile load or cyclic/seismic load, locally wall thinned pipes shall be considered pressure blow out by the internal pressure itself.

This paper introduces the failure of a uniformly thinned cylinder by an internal pressure and describes limitation on wall thinning depth to avoid pressure blow out for Class 1 piping.

NOMENCLATURE

D : Outer diameter of cylinder
e : National logarithm = 2.718
$L_{nom(t)}$: Maximum transverse extent of local thinned area
n : Strain hardening coefficient
p_B: Burst pressure for straight pipe
R_i: Pipe inner radius
R_o: Pipe outer radius
R_m: Pipe mean radius
R_{m0}: Original cylinder mean radius
S_U : Ultimate tensile strength given by construction code
S_y : Yield stress given by construction code
t : Pipe wall thickness
t_{busrt}: Wall thickness at burst
t_{nom}: Pipe nominal wall thickness
t_p : Predicted wall thickness
t_{re}: Remaining wall thickness
W: Ratio of outer and inner radius (= R_o/R_i)
b : Angle to neutral axis of thinned pipe
ε_f : Median hoop strain at failure
$\sigma_b{}^c$: Bending stress at collapse
σ_f : Failure stress
$\sigma_m{}^c$: Membrane stress at collapse
σ_m : Unintensified primary membrane stress pipe at thinned location
σ_U : Ultimate tensile strength
σ_y : Yield stress

INTRODUCTION

Wall thinning caused by the flow of water in power piping systems became a major concern to the nuclear power industries with the December 1986 rupture of a 18 inch diameter feed water line at Surry Unit 2 and the August 2004 rupture of a 22 inch diameter condensate water line at Mihama Unit 3. Since that tragic events, the need to address local wall thinning in pressure boundary materials becomes more acute.

ASME Code Case N-597-2, “Requirements for Analytical Evaluation of Pipe Wall Thinning,” provides procedures and criteria for Code Class 2 and 3 piping for the evaluation of local wall thinning that are based on Construction Code principles, including consideration of minimum wall thickness, non-uniform thickness distribution, and local wall thinning criteria based on local membrane stress, ANSI B31G methods and branch reinforcement rules [1]. These procedures and criteria have proven useful for Code Class 2 and 3 piping; but, they provide relatively little flexibility for Class 1 applications.

Recent program of full-scale experiments conducted in Japan and Korea on thinned Class 1 ferritic pipe led to the development of failure strength evaluation methodologies applicable to Class 1 piping. Burst and monotonic bending tests with internal pressure were performed on 6 inch diameter carbon steel pipe by JAERI (Japan Atomic Energy Research Institute; current Japan Atomic Energy Agency) [2]. Quasi-static bending tests without internal pressure were conducted on 4 inch diameter straight pipes, elbow and tee pipes by Hitachi and Yokohama National University [3, 4, 5]. Low cycle fatigue tests were performed on 4 inch diameter straight pipes [6] and seismic tests with internal pressure were conducted on 4 inch diameter straight pipes and 8 inch diameter elbows with in-plane, out-of-plane and mixed mode of in- and out-of-plane loading conditions [7]. In addition, numerical numerical analyses were conducted to estimate deformation behavior and failure stresses [8, 9, 10].

Prior to the failure by bending moment, tensile load or cyclic/seismic load, locally wall thinned pipes with internal pressure shall be considered pressure blow out by internal pressure itself.

This paper describes the prediction methods of burst pressure for cylinders with uniformly thinned wall thickness and examines the pressure blow out for Class 1 piping subjected to bending moment or tensile load from the view point of codification.

ANALYTICAL EVALUATION FOR CLASS 1 PIPE

ASME Code Case N-597-2 provides analytical evaluation on local wall thinning for piping items. A Class 1 but welded straight pipe, or elbow is acceptable for continued service without further evaluation when the predicted wall thickness t_p is not less than 0.875 t_{nom}, except Class 1 short radius elbow. When the t_p is less than 0.3 t_{nom}, Class 1 piping is not evaluated by the Code.

The analytical evaluation for Class 1 piping item with the predicted wall thickness between 0.875 t_{nom} and 0.3 t_{nom} is under preparation [11]. To develop analytical evaluation for pressurized piping items for the thickness between 0.875 t_{nom} and 0.3 t_{nom} subjected to external bending moment and tensile load, following equations based on net-stress approach are under discussions at the ASME Section XI Working Group on Pipe Flaw Evaluation.

For circumferentially oriented wall thinning pipe under bending moment with internal pressure shown in Fig. 1, where $((L_{nom(t)}/2R_m) + b) \leq \pi$, collapse stress σ_b^c is given by;

$$s_b^c = \frac{2S_U}{p}\left[2\,sin\,b - \frac{t_{nom} - t_p}{t_{nom}}\,sin\frac{L_{nom(t)}}{2R_i}\right] \qquad (1)$$

with

$$b = \frac{1}{2}\left(p - \frac{t_{nom} - t_p}{t_{nom}}\frac{L_{nom(t)}}{2R_i} - p\frac{s_m}{S_U}\right) \qquad (2)$$

where b is the angle to neutral axis of thinned pipe section, and S_U is the material ultimate tensile strength given by the construction code.

For longer wall thinning penetrating the compressive bending region, where $((L_{nom(t)}/2R_m) + \beta) > \pi$, the collapse bending stress σ_b^c is given by;

$$s_b^c = \frac{2S_U}{p}\left[2\left(1 - \frac{t_{nom} - t_p}{t_{nom}}\right)sin b + \frac{t_{nom} - t_p}{t_{nom}}\,sin\frac{L_{nom(t)}}{2R_i}\right] \qquad (3)$$

with

$$b = p + \frac{1}{1 - (t_{nom} - t_p)/t_{nom}}\left(\frac{\frac{t_{nom} - t_p}{t_{nom}}\frac{L_{nom(t)}}{2R_i} - p}{2} - \frac{ps_m}{2S_U}\right) \qquad (4)$$

The maximum buckling stress σ_b^c for fully circumferential wall thinning pipe subjected to bending moment is given by;

$$s_b^c = \frac{2S_U}{p}\left[2\left(1 - \frac{t_{nom} - t_p}{t_{nom}}\right)sin\,b\right] \qquad (5)$$

with

$$b = p - \frac{p}{1 - (t_{nom} - t_p)/t_{nom}}\left(\frac{t_p/t_{nom}}{2} + \frac{s_m}{2S_U}\right) \qquad (6)$$

For circumferentially oriented wall thinning pipe subjected to tensile load as shown in Fig. 2, the collapse membrane stress σ_m^c is expressed by;

$$s_b^c = S_U\left[1 - \left(\frac{t_{nom} - t_p}{t_{nom}}\right)\left(\frac{L_{nom(t)}}{2R_i p}\right) - \frac{2j}{p}\right] \qquad (7)$$

with

$$j = arcsin\left[0.5\left(\frac{t_{nom} - t_p}{t_{nom}}\right)sin\left(\frac{L_{nom(t)}}{2R_i}\right)\right] \qquad (8)$$

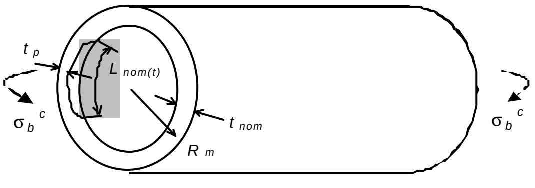

Fig. 1 Collapse bending stress for circumferentially oriented wall thinning pipe.

The failure stress for circumferentially oriented wall thinning pressurized pipes subjected to bending moment or tensile load is expressed by the above equations. These equations consist of material property, pipe size and circumferential extent of a local thinned area $L_{nom(t)}$, and does not contain the axial extent of a local thinned area in the equations.

It is anxious for the above equations about the pressure blow out. Because they do not contain limitations of lengths of axial wall thinning. Pressurized pipes might burst by its internal pressure prior to occurrence of collapse by bending moment and tensile load. Necessity of axial length limitation to prevent pressure blow is examined hereafter, using the estimation of burst pressure of a uniformly thinned pipe.

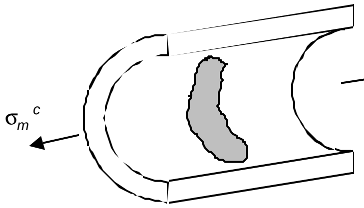

Fig. 2 Collapse membrane stress for circumferentially oriented wall thinning pipe.

BURST PRESSURE FOR THIN CYLINDER

Several formulas for predicting failure stresses for uniformly thin walled pipes subjected to only internal pressure shown in Fig. 3 were proposed in 1960's based on plastic instability theory [12, 13]. It is said that these formulas of thin walled cylinder give almost the same results when the ratio of outer radius to inner radius W is less than 1.2. When the ratio of W is around 1.6, the results become different. The formulas are introduced briefly, and pressure blow out for Class 1 piping is discussed from wall thickness at burst using these formulas.

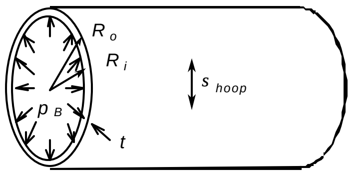

Fig. 3 Thin cylinder subjected to internal pressure.

Formula by N.L. Svensson

N.L. Svensson had developed a following formula of burst pressure for cylinders based on internal pressure analysis and experiments [14]. This equation is recommended by PVRC (The Pressure Vessel Research Council of the Welding Research Council) at the WRC Bulletin 95 in 1964.

$$\begin{aligned} p_B &= f_{c2} s_U \ln W \\ f_{c2} &= \left(\frac{0.25}{n+0.227}\right)\left(\frac{e}{n}\right)^n \qquad (9) \\ W &= R_o / R_i \end{aligned}$$

Equation (9) is applicable to thin and thick wall thickness cylinders. For a cylinder where $W \leq 1.4$, burst pressure for thin cylinder is simply expressed from Eq. (9) as;

$$p_B = f_{c2} \frac{s_U t_{burst}}{R_{m0}} \qquad (10)$$

where f_{c2} is the coefficient of plastic instability and the relation between strain hardening coefficient n and f_{c2} is given in Table 1. The value of f_{c2} decreases with increasing strain hardening coefficient n, and following burst pressure decreases.

Table 1 Relation between n and f_{c2}.

n	0.0	0.05	0.10	0.15	0.20	0.25	0.30	0.35
f_{c2}	1.155	1.102	1.062	1.024	0.987	0.952	0.919	0.888

Formula by Wesley et. al.

NUREG/CR-563 introduces a busrt pressure formula by Wesley et. al [15]. For a straight pipe with uniform wall thinning around the circumference, the burst pressure can be calculated from the equation given by;

$$p_B = \frac{s_f t_{re}}{\left[R_i + \left(t_{nom} - t_{re}\right)\right]\left(1 + 0.25 e_f\right)} \qquad (11)$$

where p_B is the pressure resulted in pipe burst in ksi, σ_f is the failure stress in ksi, t_{re} is the remaining wall thickness in cm, R_i is the initial inside radius in cm, $(t_{nom} - t_{re})$ is the thickness of pipe corroded away in cm, and ε_f is the median hoop strain at failure. Failure stress σ_f and hoop strain ε_f at failure are determined from uniaxial tensile test specimens.

Mean values for failure stress and failure strain for SA 516 grade carbon steel are shown in Table 2 [15].

Table 2 Typical failure stress and hoop strain parameter values for SA 516 grade 70 carbon steel.

Temperature F°, (C°)	Failure stress σ_f, ksi, (MPa)	Hoop strain ε_f, %
77 (25)	75.6 (519)	6.2
400 (204)	78.3 (537)	3.7
600 (316)	76.5 (525)	5.8
800 (427)	63.9 (438)	7.9

Formula by Thin Walled Cylinder Method

Burst pressure p_B for a straight cylinder with uniform thin wall thickness subjected to internal pressure is simply estimated by the following equation [12].

$$s_U = p_B\left(\frac{R_O}{t} - 1\right) \qquad (12)$$

Equation (12) is based on hoop stress. The failure mode of the cylinder is ductile fracture.

Formula by Average Radius Method

Hoop stress for a thin cylinder is given by $\sigma = pR_i/t$. The hoop stress is also expressed by $\sigma = p(R_o/t - 0.5)$, using average mean radius of $(R_o+R_i)/2$, instead of inner radius R_i. The failure pressure is written by [12];

$$s_U = p_B\left(\frac{R_O}{t} - 0.5\right) \qquad (13)$$

Formula expressed by Eq. (13) gives low burst pressure compared with thin walled cylinder method of Eq. (12).

Formula by Modified Lamè

Modified Lamè formula is similar to the formula by thin walled cylinder method. This formula is also applicable to ductile failure mode. Burst pressure for thin cylinder is given by [12];

$$s_U = p_B\left(\frac{R_O}{t} - 0.4\right) \qquad (14)$$

Modified Lamè formula of Equation (14) derived from thick cylinder of Lamè formula. Lamè formula is widely employed at a construction design for a pressure vessel.

Formula by Clavarino

Burst pressures for thin and thick wall cylinders were derived from the equivalent stress corresponding to the maximum elastic strain as follows [12];

$$s_U = p_B\left(1.3R_O^2 + 0.4R_i^2\right)/\left(R_O^2 - R_i^2\right) \qquad (15)$$

The Eq. (15) is called a method of the maximum principal strain.

Formula by Blair

Formula by Blair had developed from the maximum value at inner radius of equivalent stress of Mises yield condition. Burst pressure is estimated by the pipe geometry and the ultimate tensile strength [13]. The relation between burst pressure and pipe geometry is expressed by;

$$s_U = p_B\frac{\sqrt{W+\left(W^3+3\right)/2+W^4}}{W^2-1} \qquad (16)$$

where W is the ratio of outer and inner radius of a pipe ($=R_o/R_i$).

Formula by Sonderberg

Basic stress of Sonderberg formula is the equivalent stress of Mises yield condition, where each stress component from inside to outside radius becomes uniform at the creep condition. Burst pressure for thin cylinder is given by [12],

$$s_U = p_B\left(\sqrt{3}/2\right)\left(\frac{R_O}{t} - 0.5\right) \qquad (17)$$

WALL THICKNESS AT PRESSURE BLOW OUT

Analytical Conditions

Material data for Class 1 piping used in the calculation are JIS STS 410 (Japanese Industrial Standards: carbon steel pipes for high pressure service) which corresponds to the ASTM A333 Gr.6. The material is commonly used in Class 1 coolant piping systems in nuclear power plants in Japan. The design yield strength S_y and design ultimate tensile strength S_U at 300 C° are 183 MPa and 404 MPa, respectively. These design data of S_y and S_U are used as σ_y and σ_U in Eqs. (9) to (17) to obtain burst pressures.

Pipe dimensions for the calculations are shown in Table 3. There are three types of schedules employed, schedule 40, 80 and 160. Nominal wall thickness increases with increasing the number of schedule. The ratios of W for nominal wall thickness are about 1.05 to 1.11 for schedule 40 pipe, W= 1.12 to 1.18 for schedule 80 and W = 1.24 to 1.31 for schedule 160, respectively.

Internal pressure to be applied corresponds to the number of schedule. For example, schedule 40 pipes are used for internal pressure of 4 MPa or less. Schedule 40 pipes can be also used more than 4 MPa, if the design wall thickness satisfied with the Construction Code. However, internal pressure for the schedule pipe can not be much greater than 4 MPa. Therefore, wall thickness at burst is obtained from anticipated maximum design internal pressure of 4 MPa, 8 MPa or 16 MPa for schedule 40, 80 or 160 pipe, respectively.

Table 3 Diameter and wall thickness for various schedule pipe.

Pipe diameter, D		Nominal wall thickness, t_{nom}, mm		
inch	mm	Sch.40	Sch.80	Sch.160
4	114.3	6.0	8.6	13.5
8	216.3	8.2	12.7	23.0
12	318.5	10.3	17.4	33.3
16	406.4	12.7	21.4	40.5
20	508.0	15.1	26.2	50.0
24	609.6	17.4	30.9	59.5
30	726.0	17.4	38.1	-

Wall Thickness at Burst for Various Pipe Diameter

The formula of Svensson was recommended by PVRC at the WRC Bulletin 95 in 1964. In addition, conservative values are obtained among other formulas, as will be mentioned later. Therefore, wall thickness at burst for various diameter pipe was calculated using Eq. (10).

Table 4 shows the calculation results of wall thickness t_{burst} at burst for each diameter schedule pipe under the internal pressure of 4 MPa for schedule 40, 8 MPa for schedule 80 or 16 MPa for schedule 160 pipe. The ratio of outer radius to inner radius for t_{burst} is W = 1.01, 1.02 and 1.04 for schedule 40, 80 and 160 pipe, respectively. The values of these W are considered to be satisfied with the condition of thinned walled cylinder.

The material constants for STS 410 used in the calculation are σ_U = 404 MPa, n = 0.624 and f_{c2} = 0.942. Wall thickness at burst is normalized by the nominal wall thickness t_{nom} in Table 4. As the ratios of t_{burst} / t_{nom} are around 0.1 to 0.2, it can be seen that t_{nom} have enough wall thickness against pipe burst.

Table 4 Wall thickness at burst calculated by Svenson Formula.

Sch.	p_B, MPa	D, in.	t_{nom}, mm	t_{burst}, mm	t_{burst} / t_{nom}
40	4	4	6.0	0.60	0.100
		8	8.2	1.13	0.138
		12	10.3	1.67	0.162
		16	12.7	2.12	0.167
		20	15.1	2.66	0.176
		24	17.4	3.19	0.183
		30	17.4	3.80	0.218
80	8	4	8.6	1.19	0.138
		8	12.7	2.25	0.177
		12	17.4	3.31	0.190
		16	21.4	4.23	0.198
		20	26.2	5.28	0.202
		24	30.9	6.34	0.205
		30	38.1	7.55	0.198
160	16	4	13.5	2.35	0.174
		8	23.0	4.45	0.194
		12	33.3	6.56	0.197
		16	40.5	8.37	0.207
		20	50.0	10.46	0.209
		24	59.5	12.55	0.211

Figures 4, 5 and 6 shows the relationship between t_{burst}/t_{nom} and pipe diameter for schedule 40, 80 and 160 pipes, with the criteria of wall thinning of the ASME Code Case N-597-2. Local wall thickness t_p in Figs 4, 5 and 6 means the predicted thickness at the next schedule examination given by the Code Case N-597-2. The line of $t_p = 0.875\ t_{nom}$ is a boundary of acceptance standard for Class 1, 2 and 3 piping. If $t_p > 0.875\ t_{nom}$, the wall thickness of the pipe is acceptable to continue operation without any further analytical evaluation. The line of $t_p = 0.3\ t_{nom}$ is a boundary of acceptance criteria for Class 1 piping. If $t_p \leq 0.3\ t_{nom}$, the wall thickness in a pipe is not allowed using the Code Case.

The ratios of wall thickness t_{burst}/t_{nom} are almost the same among the pipe schedules. The ratio of wall thickness t_{burst}/t_{nom} is slightly increasing with increasing pipe diameter. However, the values of t_{burst}/t_{nom} are shown to be less than 0.3 t_{nom}.

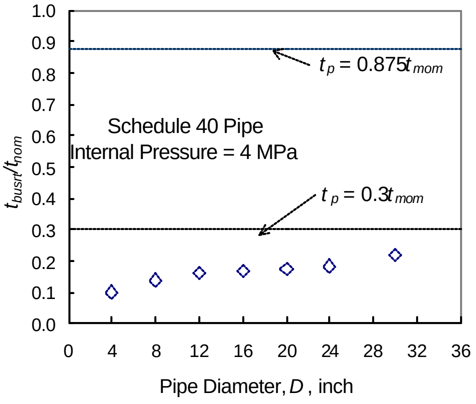

Fig. 4 Wall thickness at burst for schedule 40 pipes.

Comparison of Burst Thickness for Various Formula

Wall thickness at burst for thin cylinder with different diameter and schedule were obtained under the internal pressures using the formula of Svenson. Although Svenson's formula is reliable, wall thickness at burst are checked by other formulas to compare the t_{burst} given by Svenson's formula. 30 inch diameter schedule 80 pipe under the pressure of 8 MPa is selected arbitrary for calculation. At the calculation by the formula of Wesley et. al, the median hoop strain ε_f is used 0.058 at 600 F°, shown in Table 2. However, failure stress σ_f is used 404 MPa (58.7 ksi) instead of 76.5 ksi in Table 2 for conservative estimation.

Comparison of wall thickness at burst by internal pressure for 30 inch diameter schedule 80 pipe is shown in Table 5. The wall thickness for burst estimated by Svenson's formula gives conservative value. However, the thickness t_{burst} are almost the same. The ratios of t_{burst} /t_{nom} are around 0.16 to 0.2.

Table 5 Burst wall thickness for 30 inch diameter schedule 80 pipes under the pressure of 8 MPa

Formula	t_{burst}, mm	t_{burst} /t_{nom}
Svensson	7.55	0.198
Wesley et al.	7.15	0.188
Thin cylinder	7.04	0.185
Average radius	7.12	0.187
Modified Lamè	7.13	0.187
Clavarino	6.11	0.160
Blair	7.09	0.186
Sonderberg	6.17	0.162

PRESSURE BLOW OUT FOR CLASS 1 PIPES

It can be seen in Tables 4 and 5 that pressurized pipe might burst if the pipe thickness is less than about 20% of nominal wall thickness in case of anticipated maximum design pressure of each schedule.

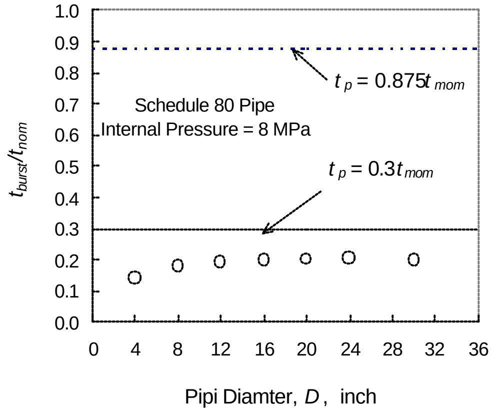

Fig. 5 Wall thickness at burst for schedule 80 pipes.

The ASME Code Case N-597-2 defines that the evaluation of t_p less than 0.3 t_{nom} for Class 1 piping item is beyond the scope of this Code Case. From the calculation results shown in Figs 4, 5 and 6, it is reasonable that wall thickness less than 0.3 t_{nom} does not allow to use the Code Case. Therefore, Code Class 1 piping item does not occur pressure blow out under the condition of $t_p > 0.3\ t_{nom}$. The criteria of $t_p > 0.3\ t_{nom}$ is considerably important to avoid catastrophic failure. On the other hand, the analytical evaluation for Class 2 piping item is applicable for $t_p > 0.2\ t_{nom}$. As the analytical evaluation for Class 2 piping was determined based on the construction code, the consideration on the pressure blow out is already included in the Code Case.

It is obvious that, prior to collapse by bending moment or tensile load, a pressurized pipe does not occur pressure blow out under the condition of $t_p > 0.3\ t_{nom}$. It is not necessary to add limitation of axial length into Eqs. (1) to (8).

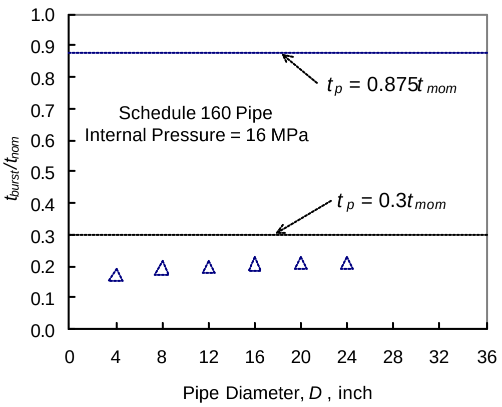

Fig. 6 Wall thickness at burst for schedule 160 pipes

CONCLUSIONS

Codification of collapse stresses to determine allowable wall thinning in Class 1 piping item subjected to bending moment or tensile load is under discussion at ASME Code Section XI Working Group on Pipe Flaw Evaluation. It was anxious that pressure blow out occurs prior to collapse of bending or tensile load. However, it was shown by this paper that pressure blow out for Class 1 piping is unlikely to occur under the condition of $t_p > 0.3\ t_{nom}$. If t_p has enough accuracy, it can be assured that it is not necessary for applied bending or tensile stress at collapse equations to contain the limitation of axial wall thinning length.

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REFERENCES

1. ASME B&PV Code Section XI, Code Case N-597-2, Requirements for Analytical Evaluation of Pipe Wall Thinning, Nov. 2003.
2. Isozaki, T., Shibata, K., et al., May 1993, “Technical Report on the Piping Reliability Proving Tests at the Japan Atomic Energy Research Institute,” JAERI-M 93-076, (in Japanese).
3. Miyazaki, K., Kanno, S., Ishiwata, M., Hasegawa, K., Ahn, S. H., and Ando, K., 1999, “Fracture Behavior of Carbon Steel Pipe with Local Wall Thinning Subjected to Bending Load,” *Nuclear Engineering & Design*, vol. 191, pp.195-204.
4. Ahn, S. H., Nam, K. W., Yoo, Y. S., Ando, K., Ji, S. H., Ishiwata, M., and Hasegawa. K., 2002, “Fracture Behavior of Straight Pipe and Elbow with Local Wall Thinning,” *Nuclear Engineering & Design*, vol. 211, pp.91-103.
5. Takahashi, K., Ando, K., Hisatsune, M., and Hasegawa, K., “Fracture and Deformation Behaviors of the Tee Pipe with Local Wall Thinning under Monotonic Bending”, ASME PVP 2004, Vol.480, pp.381-386.
6. Hasegawa, K., Sakata, K., Miyazaki, K and Kanno, S., 2002, “Fatigue Strength for Pipes with Allowable Flaws and Design Fatigue Curve,” *Int. J. of Pressure Vessel and Piping*, vol. 79, pp.37-44.
7 Hasegawa, K., Miyazaki, K., and Nakamura, I., Failure Mode and Failure Strengths for Wall Thinning Straight Pipes and Elbows Subjected to Cyclic Loading, ASME PVP05, Denver, CO., July 2005, PVP 2005-71358.
8. Shin, D. J., Choi, J. B. and Kim, Y. J., 2004, “Failure Strength Assessment of Pipes with Local Wall Thinning under Combined Loading based on Finite Element Analyses,” *J of Pressure Vessel Technology*, vol. 126, pp.179-183.
9. Kim, Y. J, Shim, D. J., Lim, H. and Kim, Y. J., 2004, “Reference Stress based on Approach to Predict Failure Strength of Pipes with Local Wall Thinning under Single Loading,” *J of Pressure Vessel Technology*, vol. 126, pp. 194-201.
10. Kim, Yun-Jae., and Kim, Young-Jin, “Reference Stress Approach for Failure Strength Estimations of a Pipe with Local Wall Thinning, ASME PVP05, Denver, CO., July 2005, PVP2005-71551.
11. Hasegawa, K., Wilkowski, G., Goyette, L. and Scarth, D., 2004, “Development of Analytical Evaluation Procedures and Acceptance Criteria for Pipe Wall Thinning in ASME Code Section XI,” *Proceedings of 2004 ASME Pressure Vessels and Piping Conference*, San Diego, PVP-Vol.474, pp.83-88.
12. JSME (The Japan Society of Mechanical Engineers) Handbook, Strength of Materials, 2001, p.102, (in Japanese).
13. Utoguchi, E., and Okamura, H.., “Basic Formulas for Wall Thickness Design on High Pressurized Cylinders, HPI, Vol. 3, No.3, 1965, pp.476-487, (in Japanese).
14. WRC Bulletin 95, 1964.
15.NUREG/CR-5632, Incorporating Aging Effects into Probabilistic Risk assessment – A Feasibility Study Utilizing Reliability Physics Models, Aug. 2002.