Table 5-16. Quantifying Imperfections.

Imperfection type	Symbol	Unit	Formula	Note
Annular gap	g	Inch	$g = s \cdot P/2\pi \leq g_{max}$	Recommended limit for State I: $g_{max} = 0.04$ in.
4H ovality	Ov_{4H}	—	$Ov_{4H} = \dfrac{D_{max} - D}{D}$	In a circular rigid pipe: $Ov_{4H} = \theta$
Hinge rotation angle	θ	Radians	$\theta = \dfrac{w_{crack}/2}{t_p}$	In a noncircular rigid pipe
Elliptical ovality	Ov_E	—	$Ov_E = \dfrac{D_{max} - D_{min}}{D_{max} + D_{min}}$	In a flexible circular pipe
Flattening	φ	Radians	$2\varphi \leq 0.785$ (45°) $2\varphi = 0.262$ (15°) intr.	The angle 2φ is limited to 45° For intrusions, $2\varphi = 15°$
Intrusion (amplitude)	w	Inch	$2\% \leq w/R \leq 5\%$	The ratio w/R is between 2% and 5%

where

t = Liner thickness, in.;

t_p = Thickness of host pipe's wall, in.;

s = Liner's material shrinkage, %. Recommended values for estimating the gap for all liner materials: $s = 0.50\%$;

P = Perimeter of the liner at its neutral axis, in., calculated as follows: $P = P_i - \pi \cdot t$;

P_i = Inside the perimeter of the host pipe, in.;

R = Radius of the arc where a blister is likely to develop (measured to the liner's neutral axis), in., calculated as follows: $R = R_i - t/2$;

R_i = Inside radius of the host pipe's arc where a blister is developing, in.;

D = Host pipe's inside diameter (ID), as originally designed and constructed, in. In circular pipes only;

D_{max} = Host pipe's maximum inside diameter (horizontal), in circular pipes showing ovality, in.;

D_{min} = Host pipe's minimum inside diameter (horizontal), in circular pipes showing ovality, in.;

θ = Hinge rotation angle, radians; and

w_{crack} = Hinge crack opening width, in.

hinge rotation angle, are for convenience shown in Figure 5-20, and are included in formulas presented in Steps 7 and 8, but they are only used in Design for States II and III (rigid pipes with hinge fractures are not designed for State I).

Note that the required liner thickness calculated in this design procedure is very sensitive to the value of annular gap. The table shows the limit values of some imperfections in the design (for instance, if flattening develops beyond $2\varphi = 45°$, the pipe should not be lined).

Step 7. Calculate Imperfection Coefficients

In this step, the following imperfection coefficients are calculated for quantified imperfections, using the formulas in Tables 5-17 through 5-20:

δ_g = Imperfection coefficient for annular gap, unitless;

δ_{4H} = Imperfection coefficient for 4-H ovality in a circular host pipe;

δ_φ = Imperfection coefficient for local flattening, unitless; and

δ_w = imperfection coefficient for local intrusion, unitless.

Table 5-17. Annular Gap Coefficient, δ_g, Unitless.

Pipe shape	Homogeneous liner material and structured wall	Homogeneous liner material and plain wall
Any	$\delta_g = \frac{1}{k^{0.4}} \cdot \frac{2g}{R} \cdot \left(\frac{\pi}{2} \cdot \frac{A}{I} \cdot \frac{R^3}{P}\right)^{0.6}$	$\delta_g = 11.65 \cdot \frac{g}{k^{0.4}} \cdot \frac{R^{0.8}}{t^{1.2} \cdot P^{0.6}}$
Circular	$\delta_g = 0.87 \cdot g \cdot R^{0.2} \cdot \left(\frac{A}{I}\right)^{0.6}$	$\delta_g = 3.87 \cdot \frac{g}{R} \cdot \left(\frac{R}{t}\right)^{1.2}$
3 × 2 Egg	$\delta_g = 1.11 \cdot g \cdot R^{0.2} \cdot \left(\frac{A}{I}\right)^{0.6}$	$\delta_g = 4.93 \cdot \frac{g}{R} \cdot \left(\frac{R}{t}\right)^{1.2}$
Elliptical	$\delta_g = 1.07 \cdot \frac{1}{k^{0.4}} \cdot \left(\frac{A}{I}\right)^{0.6} \cdot \frac{a^{1.6}}{b^{0.8} \cdot (a^2 + b^2)^{0.3}}$	$\delta_g = 4.76 \cdot \frac{g}{k^{0.4}} \cdot \frac{a^{1.6}}{t^{1.2} \cdot b^{0.8} \cdot (a^2 + b^2)^{0.3}}$

Note: Circular: $k = 1$; 3×2 egg: $k = 2$. Height = R, width = 2R/3, perimeter = $2.643 \cdot R$, $2\alpha = 0.644$ radians; elliptical: $k = 1$ or 2; ellipse axes: a is semimajor, and b is semiminor.

Table 5-18. 4H Ovality Coefficient, δ_{4H}, Unitless.

Pipe shape	Homogeneous liner material and structured wall	Homogeneous liner material and plain wall
Circular	$\delta_{4H} = 0.273 \cdot \theta \cdot \left(\frac{A}{I} \cdot R^2\right)^{0.2}$	$\delta_{4H} = 0.448 \cdot \theta \cdot \left(\frac{R}{t}\right)^{0.4}$
Any	$\delta_{4H} = 0.394 \cdot k^{0.2} \cdot \theta \cdot \left(\frac{A}{I} \cdot \frac{R^3}{P}\right)^{0.2}$	$\delta_{4H} = 0.648 \cdot k^{0.2} \cdot \theta \cdot \left(\frac{R^3}{t^2 \cdot P}\right)^{0.2}$
3 × 2 Egg	$\delta_{4H} = 0.324 \cdot k^{0.2} \cdot \theta \cdot \left(\frac{A}{I} \cdot R^2\right)^{0.2}$	$\delta_{4H} = 0.534 \cdot k^{0.2} \cdot \theta \cdot \left(\frac{R}{t}\right)^{0.4}$
Elliptical	$\delta_{4H} = 0.292 \cdot k^{0.2} \cdot \theta \cdot \frac{\left(\frac{A}{I}\right)^{0.2} \cdot a^{1.2}}{b^{0.6} \cdot (a^2 + b^2)^{0.1}}$	$\delta_{4H} = 0.481 \cdot k^{0.2} \cdot \theta \cdot \frac{a^{1.2}}{t^{0.4} \cdot b^{0.6} \cdot (a^2 + b^2)^{0.1}}$

Note: Circular: $Ov_{4H} = \theta$.

where

R = Radius of arc where a blister is likely to develop measured to the liner's neutral axis, in.;

A = Cross-sectional area of the unit length of the liner, in.^{2}/in.;

I = Area moment of inertia of the unit length of the liner, in.^{4}/in.; and

P = Perimeter of the liner at its neutral axis, in.

Only imperfections found in pipe arcs where blisters develop should be taken into calculation.

Step 8. Calculate Correction Factors

Three correction factors that will be used in Step 9 are calculated in this step using the formulas in Table 5-21. They are (1) Reduction factor for critical buckling pressure. The formulas for calculating this factor are provided in Table 5-22 for individual imperfections and in Table 5-23

Table 5-19. Local Flattening Coefficient, δ_φ, Unitless.

Pipe shape	Homogeneous liner material and structured wall	Homogeneous liner material and plain wall
Any	$\delta_\varphi = 0.394 \cdot k^{0.2} \cdot \varphi \cdot \left(\frac{A}{I} \cdot \frac{R^3}{P}\right)^{0.2}$	$\delta_\varphi = 0.648 \cdot k^{0.2} \cdot \varphi \cdot \left(\frac{R^3}{t^2 \cdot P}\right)^{0.2}$
Circular	$\delta_\varphi = 0.273 \cdot \varphi \cdot \left(\frac{A}{I} \cdot R^2\right)^{0.2}$	$\delta_\varphi = 0.448 \cdot \varphi \cdot \left(\frac{R}{t}\right)^{0.4}$
Elliptical	$\delta_\varphi = 0.292 \cdot k^{0.2} \cdot \varphi' \cdot \frac{\left(\frac{A}{I}\right)^{0.2} \cdot a^{1.2}}{b^{0.6} \cdot \left(a^2 + b^2\right)^{0.1}}$	$\delta_\varphi = 0.481 \cdot k^{0.2} \cdot \varphi' \cdot \frac{a^{1.2}}{t^{0.4} \cdot b^{0.6} \cdot \left(a^2 + b^2\right)^{0.1}}$

Note: Elliptical: $\varphi' = \tan^{-1}\left(\frac{b^2}{a^2} \cdot \tan\varphi\right)$.

Table 5-20. Local Intrusion Coefficient, δ_w, Unitless.

Pipe shape	Homogeneous liner material and structured wall	Homogeneous liner material and plain wall
Any	$\delta_w = 0.155 \cdot k^{0.4} \cdot \left(\frac{w}{R} - \frac{\varphi^2}{2}\right) \cdot \left(\frac{A}{I} \cdot \frac{R^3}{P}\right)^{0.4}$	$\delta_w = 0.42 \cdot k^{0.2} \cdot \left(\frac{w}{R} - \frac{\varphi^2}{2}\right) \cdot \left(\frac{R^3}{t^2 \cdot P}\right)^{0.4}$ If $\delta_w < 0$ then $\delta_w = 0$
Circular	$\delta_w = 0.0745 \cdot \left(\frac{w}{R} - \frac{\varphi^2}{2}\right) \cdot \left(\frac{A}{I} \cdot R^2\right)^{0.4}$	$\delta_w = 0.2 \cdot \left(\frac{w}{R} - \frac{\varphi^2}{2}\right) \cdot \left(\frac{R}{t}\right)^{0.8}$

Table 5-21. Correction Factors, Unitless.

Correction factor for	Symbol	Type	Value/formula
Critical buckling pressure	κ_p	Reduction	Use formula in Table 5-22 or Table 5-23
Critical bending moment	κ_M	Amplification	$\kappa_M = 1.4$ for flattening $\kappa_M = 1.6$ for intrusion $\kappa_M = 1.1$ for all other imperfections
Hoop force	$\kappa_{N,4h}$	Amplification	$\kappa_{N,4h} = 1 + 1{,}63 \cdot \delta_{4H} + 1.17 \cdot \delta_{4H}^2$

for combined imperfections. Note that combined imperfections have a much more pronounced effect on the critical buckling pressure than on individual imperfections. (2) Amplification factors for critical bending moment and hoop force. The amplification factors will be used in the formulas for critical bending moment and hoop force.

Step 9. Calculate Design Critical Buckling Pressure, Maximum Bending Moment, and Hoop Force
Design critical buckling pressure and the associated critical bending moment and critical hoop force in the liner are calculated next. The Glock–Thépot formula for the critical buckling pressure (see Section 5.2.8 and Table 5-3) is provided in Table 5-24 for homogeneous liner materials,

Table 5-22. Reduction Factor for Critical Buckling Pressure, κ_p, Unitless. Individual Imperfections.

Imperfection	Symbol	Reduction factor
Annular gap	$\kappa_{p,g}$	$\kappa_{p,g} = \frac{1}{1+0.38\cdot\delta_g}$
Ovality (4H)	$\kappa_{p,4H}$	$\kappa_{p,4H} = \frac{1}{1+3.23\cdot\delta_{4H}+21.2\cdot\delta_{4H}^2}$
Ovality (elliptical)	$\kappa_{p,el}$	$\kappa_{p,el} = \left[\frac{1-Ov_{el}}{(1+Ov_{el})^2}\right]^{1.8}$
Flat section	$\kappa_{p,\varphi}$	If $\delta_\varphi < 0.13$, then $\kappa_{p,\varphi} = 1$ If $0.13 < \delta_\varphi < 0.8$, then $\kappa_{p,\varphi} = -3.4\cdot\delta_\varphi^{\,4} + 8.8\cdot\delta_\varphi^{\,3} - 6.97\cdot\delta_\varphi^{\,2} + 0.747\cdot\delta_\varphi + 1$ If $\delta_\varphi > 0.8$, then FEA recommended
Intrusion (w/flat section)	$\kappa_{p,w}$	$\kappa_{p,w} = \frac{1}{1+4.5\cdot\delta_w}\cdot\kappa_{p,\varphi}$

Table 5-23. Reduction Factor for Critical Buckling Pressure, κ_p, Unitless. Combined Imperfections.

Imperfections	Symbol	Global reduction factor
Gap and ovality (4H)	$\kappa_{p,g\text{-}4H}$	$\kappa_{p,g\text{-}4H} = \frac{1}{1+0.38\cdot\delta_g+1.3\cdot\delta_g\cdot\delta_{4H}+3.23\cdot\delta_{4H}+21.2\cdot\delta_{4H}^2}$
Gap and ovality (elliptical)	$\kappa_{p,g\text{-}el}$	$\kappa_{p,g\text{-}el} = \kappa_{p,g}\cdot\kappa_{p,el}$
Gap and flat section	$\kappa_{p,g\text{-}\varphi}$	$\kappa_{p,g\text{-}\phi} = \frac{1}{1+0.38\cdot\delta_g-0.33\cdot\delta_g\cdot\delta_\varphi-0.08\cdot\delta_g\cdot\delta_\varphi^{\,2}}\cdot\kappa_{p,\phi}$
Gap and intrusion	$\kappa_{p,g\text{-}w}$	$\kappa_{p,g\text{-}w} = \frac{1}{1+0.38\cdot\delta_g-0.42\cdot\delta_g\cdot\delta_{7.5^\circ}-0.5\cdot\delta_g\cdot\delta_w}\cdot\kappa_{p,w}$

for circular and selected noncircular pipe shapes (3 × 2 egg, elliptical), and for structured or plain liner wall. The maximum bending moment and the hoop force in the liner (see Section 5.2.7) are calculated with the formulas provided in Table 5-25, both per unit length of liner.

Step 10. Calculate Material Design Flexural Modulus, Strength, and Corrosion Strain

Design material stiffness, strength, and elongation are calculated using the formulas in Table 5-26. Note that the material elongation is only important for liner materials that are sensitive to SCC, for example, GRP liners or CIPP made with glass fiber–reinforced tube material.

Step 11. Calculate Load: Groundwater Pressure (Service and Factored)

The service groundwater pressure acting on the liner is calculated as the hydrostatic pressure of groundwater at depth corresponding to the center of the blister (Figure 5-7). This pressure

Table 5-24. Design Critical Buckling Pressure, $p_{cr,w,d}$ Using the Thépot Analytical Model.

Pipe shape	Homogeneous material and structured wall	Homogeneous material and plain wall
Any	$p_{cr,w,d} = 2.02 \cdot \frac{k^{0.4}}{1-\nu^2} \cdot \frac{E_{50,d} \cdot I^{0.6} \cdot A^{0.4}}{P^{0.4} \cdot R^{1.8}} \cdot \kappa_p$	$p_{cr,w,d} = 0.455 \cdot \frac{k^{0.4}}{1-\nu^2} \cdot \frac{E_{50,d} \cdot t^{2.2}}{P^{0.4} \cdot R^{1.8}} \cdot \kappa_p$
Circular	$p_{cr,w,d} = 0.97 \cdot \frac{E_{50,d}}{1-\nu^2} \cdot \frac{I^{0.6} \cdot A^{0.4}}{R^{2.2}} \cdot \kappa_p$	$p_{cr,w,d} = 0.218 \cdot \frac{E_{50,d}}{1-\nu^2} \cdot \frac{t^{2.2}}{R^{2.2}} \cdot \kappa_p$
3 × 2 Egg	$p_{cr,w,d} = 1.81 \cdot \frac{E_{50,d}}{1-\nu^2} \cdot \frac{I^{0.6} \cdot A^{0.4}}{R^{2.2}} \cdot \kappa_p$	$p_{cr,w,d} = 0.407 \cdot \frac{E_{50,d}}{1-\nu^2} \cdot \frac{t^{2.2}}{R^{2.2}} \cdot \kappa_p$
Ellipt.	$p_{cr,w,d} = 1.11 \cdot \frac{k^{0.4}}{1-\nu^2} \cdot \frac{E_{50,d} \cdot I^{0.6} \cdot A^{0.4} \cdot b^{1.8}}{a^{3.6} \cdot \left(a^2+b^2\right)^{0.2}} \cdot \kappa_p$	$p_{cr,w,d} = 0.25 \frac{k^{0.4}}{1-\nu^2} \cdot \frac{E_{50,d} \cdot t^{2.2} \cdot b^{1.8}}{a^{3.6} \cdot \left(a^2+b^2\right)^{0.2}} \cdot \kappa_p$

Note: Circular: k = 1; 3 × 2 egg: k = 2; height = R, width = 2R/3, perimeter = 2.643·R; elliptical: k = 1 or 2; ellipse axes: a is semimajor, and b is semiminor.

Table 5-25. Design Critical Bending Moment, $M_{cr,w,d}$, and Hoop Force, $N_{cr,w,d}$, per Unit Length of the Liner.

Pipe shape	Parameter	Unit	Homogeneous material and structured wall	Homogeneous material and plain wall
Any	Bending moment	Lb · in./in.	$M_{cr,w,d} = 1.2 \cdot \frac{E_{50,d}}{1-\nu^2} \cdot \frac{I}{R} \cdot \kappa_M$	$M_{cr,w,d} = 0.1 \cdot \frac{E_{50,d}}{1-\nu^2} \cdot \frac{t^3}{R} \cdot \kappa_M$
Any	Hoop force	lbs/in.	$N_{cr,w,d} = 1.26 \cdot p_{cr,w,d} \cdot R \cdot \kappa_{N,4h}$	(same as general case)

where

$E_{50,d}$ = Design long-term (50 year) flexural modulus of the liner material, psi;

ν = Poisson's ratio of the liner material, unitless; and

R = Radius of arc where a blister is likely to develop measured to the liner's neutral axis, in.

is increased by applying the load factor to obtain the factored groundwater pressure, which is used in the LRFD for the limit state buckling stability check. The service and factored groundwater pressure are calculated using formulas provided in Table 5-27; recommendations how to select parameters in the formulas follow.

Step 12. Calculate Load Effects

The maximum bending moment and the hoop force in the liner are the functions of groundwater pressure acting on the liner [see about the load effects from groundwater pressure in critical shapes (Figure 5-11)].

The formulas for calculating the maximum bending moment and the hoop force in the liner at the factored groundwater pressure are provided in Table 5-28; the formulas to calculate the associated stresses and tensile strain in the liner are in Table 5-29.

Table 5-26. Liner's Design Resistance Parameters.

Parameter	Symbol	Unit	Formula
Design long-term flexural modulus	$E_{50,d}$	psi	$E_{50,d} = \Phi_{LM} \cdot E_{50}$
Design long-term flexural strength	$\sigma_{F,50,d}$	psi	$\sigma_{F,50,d} = \Phi_{LF} \cdot \sigma_{F,50}$
Design corrosion strain limit*	$\varepsilon_{L,d}$	in./in.	$\varepsilon_{L,d} = \Phi_{L\varepsilon} \cdot \varepsilon_{L}$

*Important for liner materials that are sensitive to stress corrosion cracking.

where

$\sigma_{F,50,d}$ = Design long-term (50 year) flexural strength of the liner material, psi;
ε_L = Nominal long-term elongation of the liner material, in/in.; see *;
Φ_{LM} = LRFD reduction factor on the liner's long-term flexural modulus, unitless;
Φ_{LF} = LRFD reduction factor on the liner's long-term flexural strength, unitless; and
$\Phi_{L\varepsilon}$ = LRFD reduction factor on the liner's SCC resistance, unitless.

Table 5-27. Service and Factored Groundwater Pressure.

Parameter	Symbol	Unit	Formula
Service groundwater pressure	p_w	Psi	$p_w = \gamma_w \cdot (H_w - H_b)$
Factored groundwater pressure	$p_{w,u}$	Psi	$p_{w,u} = \gamma_{GW} \cdot p_w$

where

γ_w = Hydrostatic pressure gradient, 0.434 psi/ft;
H_w = Head of water above the invert, ft;
H_b = Head of the center of the blister above invert, ft; and
γ_{GW} = LRFD load factor on the groundwater pressure, unitless.

Table 5-28. Factored Bending Moment and Hoop Force in the Liner.

Parameter	Symbol	Unit	Formula
Factored maximum bending moment, per unit length of the liner	$M_{w,u}$	lbs-in./in.	$M_{w,u} = \left[1 - \left(1 - \frac{p_{w,u}}{p_{cr,w,d}}\right)^{0.5}\right] \cdot M_{cr,w,d}$
Factored hoop force, per unit length of the liner	$N_{w,u}$	lbs/in.	If $\eta \le 0.8$: $N_{w,u} = 0.8\eta \cdot N_{cr,w,d}$ If $\eta > 0.8$: $N_{w,u} = \eta^2 \cdot N_{cr,w,d}$ where $\eta = p_{w,u}/p_{cr,w,d}$

where

$p_{w,u}$ = Factored groundwater pressure, psi;
$p_{cr,w,d}$ = Design critical buckling pressure, psi;
$M_{cr,w,d}$ = Design critical bending moment per unit length of the liner, lbs·in./in.; and
$N_{cr,w,d}$ = Design critical hoop force per unit length of the liner, lbs/in.

Table 5-29. Factored Stress and Strain in the Liner.

Parameter	Symbol	Unit	Formula
Factored max flexural stress	$\sigma_{w,f,u}$	psi	$\sigma_{w,f,u} = \frac{6 \cdot M_{w,u}}{t^2}$
Factored hoop stress	$\sigma_{w,h,u}$	psi	$\sigma_{w,h,u} = \frac{N_{w,u}}{t}$
Factored compressive stress	$\sigma_{w,c,u}$	psi	$\sigma_{w,c,u} = \sigma_{w,f,u} + \sigma_{w,h,u}$
Factored tensile strain*	$\varepsilon_{w,u}$	in./in.	$\varepsilon_{w,u} = \frac{-\sigma_{w,f,u} + \sigma_{w,h,u}}{E_{50d}} \cdot \left(1 - \nu^2\right)$

*Important for liner materials that are sensitive to stress corrosion cracking.

where

E_{50} = Long-term (50 year) modulus of the liner, psi;

ν = Poisson's ratio for the liner material, unitless; and

t = Liner thickness, in.

Step 13. Limit States: Buckling, Strength, and Capacity/Demand Ratios

The liner with assumed thickness can now be checked for material strength limit states. The basic requirements for buckling stability (see Section 5.2.8) and flexural strength and corrosion strain (see Section 5.2.12) are shown in Table 5-30. For checking the limit states in the iterative procedure, the CDRs are calculated. If all applicable limit state criteria are met, the iterative procedure is terminated.

Steps 14 and 14b. Check All CDRs

If any CDR in Step 14 is lower than required, the corresponding limit state is not satisfied and the assumed liner thickness is insufficient. The procedure goes to Step 14b where the liner thickness is increased and a new iteration initiated.

Table 5-30. Limit States and Capacity/Demand Ratios.

Limit state	Parameter	LRFD requirement	Capacity demand ratio	Limit state criterion
Buckling stability	Groundwater pressure	$p_{cr,w,d} \geq p_{w,u}$	$CDR_1 = \frac{p_{cr,w,d}}{p_{w,u}}$	$CDR_1 \geq 1$
Material strength	Compressive stress	$\sigma_{F,50,d} \geq \sigma_{w,c,u}$	$CDR_2 = \frac{\sigma_{F,50,d}}{\sigma_{w,c,u}}$	$CDR_2 \geq 1$
Stress corrosion cracking*	Flexural strain (elongation)	$\varepsilon_{L,d} \geq \varepsilon_{w,u}$	$CDR_3 = \frac{\varepsilon_{L,d}}{\varepsilon_{w,u}}$	$CDR_3 \geq 1$

*Important for liner materials that are sensitive to stress corrosion cracking.

where

CDR_1 = Capacity demand ratio for buckling pressure, unitless;

CDR_2 = Capacity demand ratio for compressive stress, unitless; and

CDR_3 = Capacity demand ratio for flexural strain (elongation), unitless.

Steps 15 and 15b. Check CDR_1 *and* CDR_2

If both CDR_1 and CDR_2 are much greater than 1.0 in Step 15, the assumed liner thickness is greater than what is minimally required. The procedure goes to Step 15b where the thickness is decreased and a new iteration initiated.

5.8.4.5 End of the Design Procedure (Critical Shape). If all applicable limit state criteria are met, the assumed liner thickness is the solution of the design procedure.

5.8.4.6 How to Assume Liner Thickness for Iterations. The choice of assumed liner thickness for the first iteration can ensure that the iterative design procedure is convergent. By starting with a sufficiently large value, all CDRs in Step 14 will be much greater than 1.0, but CDR_1 or CDR_2 will be much greater than 1.0 in Step 15, and the liner thickness will be decreasing in successive iterations, gradually approaching the minimally required thickness. For a sufficiently large value, it is recommended to choose the liner thickness for the first iteration equal to: $t_{(1st\ iteration)} = R_{arc}/20$, where R_{arc} is the radius of arc where the blister develops (measured to the pipe wall), in.

For the second iteration, it is recommended to decrease the thickness for approximately 20% and observe the change in CDR_1 and CDR_2. If both are still much greater than 1.0, the same 20% decrease can continue in the following iterations. Once CDR_1 or CDR_2 is close to 1.0, the decrease/increase of assumed thickness should become very small, for example, 0.01 in. An illustrative example of the liner thickness changing in successive iterations is shown in Table 5-31. The iterative procedure should continue until an acceptable result is achieved.

5.8.5 Subcritical Shape Design

5.8.5.1 Design Procedure Overview. This design procedure is suitable for a liner with a subcritical shape. As a reminder, a liner shape is subcritical if the blister in the liner under increasing external (groundwater) pressure continues to increase deflection and spread out without instability. Note that

- Liner design in a circular host pipe is never subcritical.
- Liner design in a noncircular host pipe with at least one flat segment is subcritical; it can converge to critical if the length of the flat segment becomes smaller than the radius of adjacent arc.
- Liner design in a noncircular host pipe with no flat segment is, in general, critical, but in some cases, a liner can be designed with a subcritical procedure, and in some cases, a subcritical design is strongly recommended (see Steps 1 and 4).

Table 5-31. Example of Assuming Liner Thickness in Successive Iterations.*

Iteration	t (inch)	CDR_1	CDR_2	CDR_{13}	dt/t	dt (inch)
1	0.60	16.40	14.34	na	20%	0.12
2	0.48	8.99	10.13	na		0.12
3	0.36	4.05	6.19	na		0.12
4	0.24	1.26	2.04	na		0.01
5	0.23	1.11	1.57	na		0.01
6	0.22	0.97	1.04	na		0.01

**Note:* In this example, host pipe $D_i = 24$ in.; $R_{arc} = 12$ in.; acceptable result: $t = 0.23$ in.

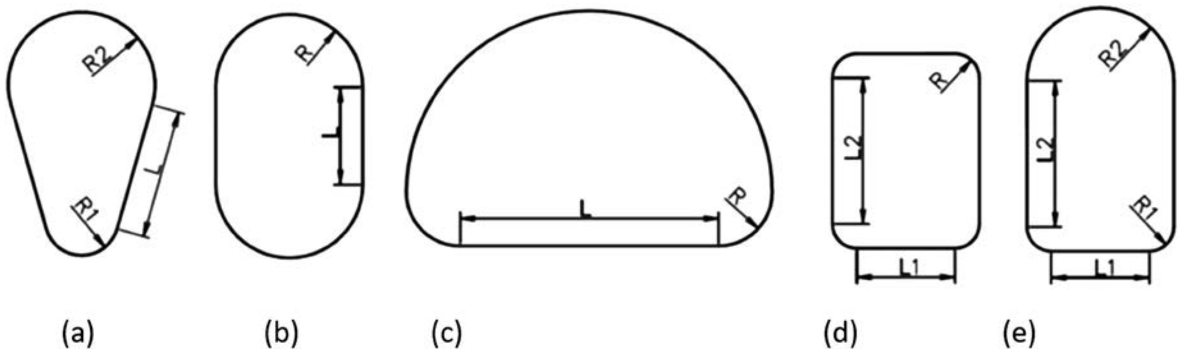

Figure 5-21. Some common pipe shapes requiring subcritical design: (a) egg-shaped, (b) oval, (c) arch with flat bottom, (d) box, (e) box shape with arch crown.

Some common pipe shapes requiring subcritical design are shown in Figure 5-21; geometry parameters are explained in Step 1.

The liner thickness design procedure is iterative. Each iteration is performed for assumed liner thickness (inches) through steps that can be grouped as follows (Figure 5-17 Right):

- Beginning steps (yellow) calculate selected model parameters and check the blister angle condition for a specified deflection limit and assumed liner thickness (as design procedure applicability confirmation).
- Part 1 steps evaluate the liner deflection.
  - Design resistance (blue) determines the external pressure on the liner at deflection limit.
  - Factored load effects (red) determines load on the liner (groundwater pressure), both service and factored.
  - Limit state (green) checks the deflection at service groundwater pressure versus deflection limit (serviceability).
- Part 2 steps evaluate the material strength.
  - Design resistance (blue) calculates the design strength of the liner based on its material properties.
  - Factored load effects (red) calculate the factored load effects for factored groundwater pressure.
  - Limit states (green) check the limit states for material strength and, if needed, initiate another iteration.

Note that the limit state verification for deflection is performed with service groundwater pressure and nominal liner resistance to external pressure, whereas the material strength limit states are checked with factored groundwater pressure and design liner strength.

5.8.5.2 Detailed Flowchart. The steps in the design procedure for critical shape are shown in the flowchart in Figure 5-22. Note that the steps marked with a star, ⋆, perform calculations that are independent of the assumed liner thickness and need to be done only once in the procedure (in the first iteration).

5.8.5.3 Beginning Steps

Step 1. Verify Geometry Conditions

The design for a subcritical shape has been developed for specific host pipe geometry conditions, and these must be verified prior to proceeding with the design. The design method assumes that a liner under sufficiently increased external pressure will develop a blister that extends

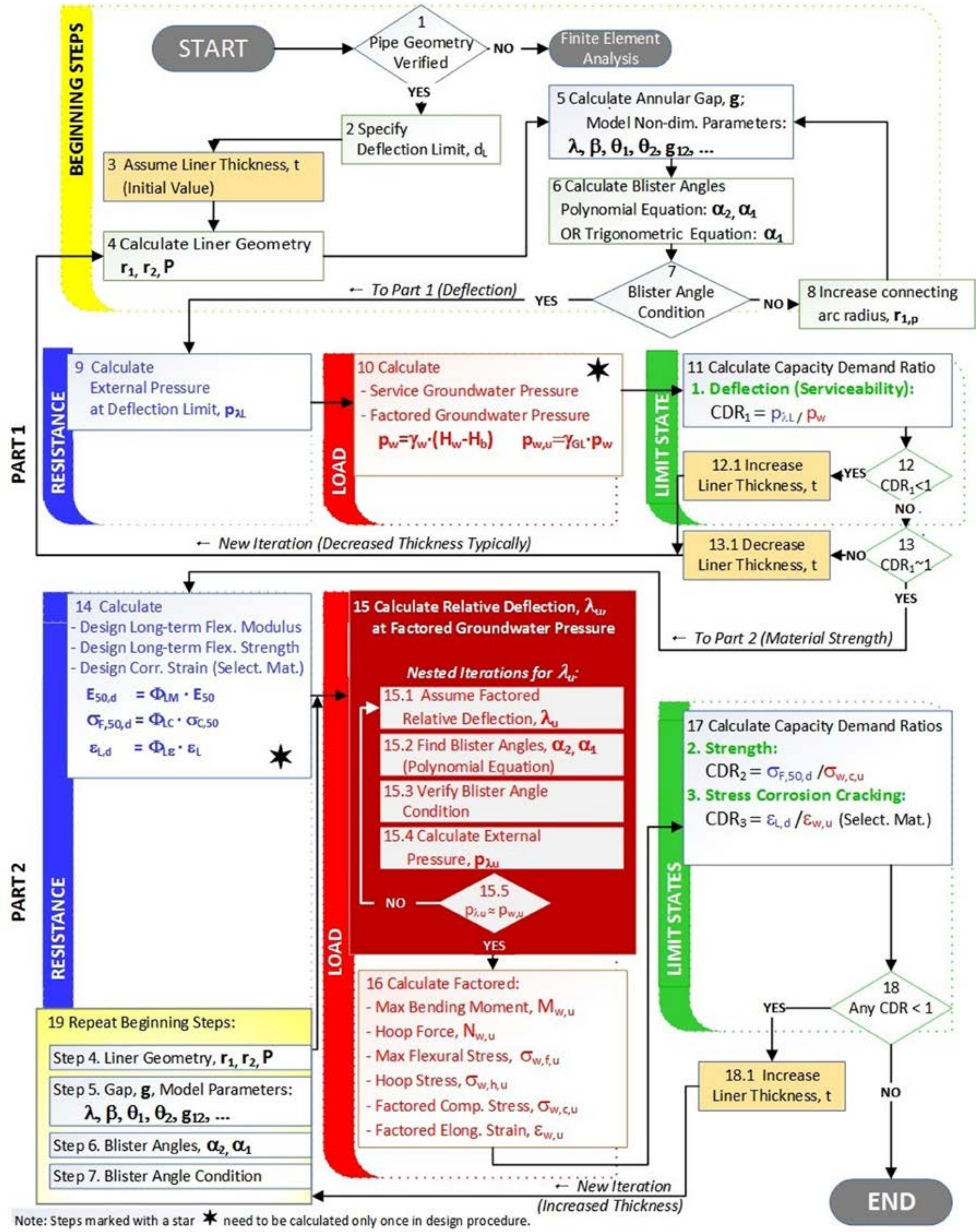

Figure 5-22. Flowchart for Design for State I—subcritical shape.

over the entire straight section and partially on the two connecting arc sections (Figure 5-23). Geometry requirements to verify this assumption are presented in Table 5-32, where two geometries can be distinguished: (1) Long straight section geometry—The length of the straight section must be greater than the connecting arcs radii. If the two arcs radii are different, then the length of the "straight" section must be greater than the greater of two. Also, if the straight section is curved, the critical angle condition ratio (see Section 5.8.4, Step 4) must be greater