G is the design specific gravity of the liquid to be stored, as specified by the Purchaser, not greater than 1.0;

Υ is the density factor of water. MPa per meter, (psi per foot) SI: 9.81/1000, USC: 62.4/144.

NOTE Derivation of the equation is from "Structural Analysis and Design of Process Equipment" by Jawad and Farr and L.P. Zick and R.V. McGrath, "Design of Large Diameter Cylindrical Shells."

Alternatively, if thickened annular plates are being solely provided as wind or seismic overturning resistance, the minimum radial distance between the inside of the shell and the edge of the plate in the remainder of the bottom shall be in accordance with 5.11.2.3 or E.6.2.1.1.3, respectively.

5.5.3 The thickness of the annular bottom plates shall not be less than the greater thickness determined using Table 5.1a and Table 5.1b for product design (plus any specified corrosion allowance) or for hydrostatic test design. Table 5.1a and Table 5.1b are applicable for effective product height of $H \times G \leq 23$ m (75 ft). Beyond this height an elastic analysis must be made to determine the annular plate thickness.

Table 5.1a—Annular Bottom-Plate Thicknesses (t_b) (SI)

Plate Thickness[a] of First Shell Course (mm)	Stress[b] in First Shell Course (MPa)			
	≤ 190	≤ 210	≤ 220	≤ 250
$t \leq 19$	6	6	7	9
$19 < t \leq 25$	6	7	10	11
$25 < t \leq 32$	6	9	12	14
$32 < t \leq 40$	8	11	14	17
$40 < t \leq 45$	9	13	16	19

[a] Plate thickness refers to the corroded shell plate thickness for product design and nominal thickness for hydrostatic test design.

[b] The stress to be used is the maximum stress in the first shell course (greater of product or hydrostatic test stress). The stress may be determined using the required thickness divided by the thickness from "a" then multiplied by the applicable allowable stress:

Product Stress = $((t_d - CA)/$ corroded $t)$ (S_d)

Hydrostatic Test Stress = $(t_t$ / nominal $t)$ (S_t)

NOTE The thicknesses specified in the table, as well as the width specified in 5.5.2, are based on the foundation providing uniform support under the full width of the annular plate. Unless the foundation is properly compacted, particularly at the inside of a concrete ringwall, settlement will produce additional stresses in the annular plate.

5.5.4 The ring of annular plates shall have a circular outside circumference, but may have a regular polygonal shape inside the tank shell, with the number of sides equal to the number of annular plates. These pieces shall be welded in accordance with 5.1.5.6 and 5.1.5.7, Item b.

5.5.5 In lieu of annular plates, the entire bottom may be butt-welded provided that the requirements for annular plate thickness, welding, materials, and inspection are met for the annular distance specified in 5.5.2.

5.6 Shell Design

5.6.1 General

5.6.1.1 The required shell thickness shall be the greater of the design shell thickness, including any corrosion allowance, or the hydrostatic test shell thickness, but the shell thickness shall not be less than the following:

Nominal Tank Diameter (m)	Nominal Tank Diameter (ft)	Nominal Plate Thickness (mm)	Nominal Plate Thickness (in.)
< 15	< 50	5	3/16
15 to < 36	50 to < 120	6	1/4
36 to 60	120 to 200	8	5/16
> 60	> 200	10	3/8

● NOTE 1 Unless otherwise specified by the Purchaser, the nominal tank diameter shall be the centerline diameter of the bottom shell-course plates.

NOTE 2 The thicknesses specified are based on erection requirements.

● NOTE 3 When specified by the Purchaser, plate with a nominal thickness of 6 mm may be substituted for 1/4-in. plate.

NOTE 4 For diameters less than 15 m (50 ft) but greater than 3.2 m (10.5 ft), the nominal thickness of the lowest shell course shall not be less than 6 mm (1/4 in.).

Table 5.1b—Annular Bottom-Plate Thicknesses (t_b) (USC)

Plate Thickness[a] of First Shell Course (in.)	Stress[b] in First Shell Course (lbf/in.^{2})			
	≤ 27,000	≤ 30,000	≤ 32,000	≤ 36,000
$t \leq 0.75$	0.236	0.236	9/32	11/32
$0.75 < t \leq 1.00$	0.236	9/32	3/8	7/16
$1.00 < t \leq 1.25$	0.236	11/32	15/32	9/16
$1.25 < t \leq 1.50$	5/16	7/16	9/16	11/16
$1.50 < t \leq 1.75$	11/32	1/2	5/8	3/4

[a] Plate thickness refers to the corroded shell plate thickness for product design and nominal thickness for hydrostatic test design.

[b] The stress to be used is the maximum stress in the first shell course (greater of product or hydrostatic test stress). The stress may be determined using the required thickness divided by the thickness from “a” then multiplied by the applicable allowable stress:

Product Stress = $((t_d - CA)/$ corroded t $)(S_d)$

Hydrostatic Test Stress = $(t_t$ / nominal t $)(S_t)$

NOTE The thicknesses specified in the table, as well as the width specified in 5.5.2, are based on the foundation providing uniform support under the full width of the annular plate. Unless the foundation is properly compacted, particularly at the inside of a concrete ringwall, settlement will produce additional stresses in the annular plate.

5.6.1.2 Unless otherwise agreed to by the Purchaser, the shell plates shall have a minimum nominal width of 1800 mm (72 in.). Plates that are to be butt-welded shall be properly squared.

5.6.1.3 The calculated stress for each shell course shall not be greater than the stress permitted for the particular material used for the course. When the allowable stress for an upper shell course is lower than the allowable stress of the next lower shell course, then either a or b shall be satisfied.

a) The lower shell course thickness shall be no less than the thickness required of the upper shell course for product and hydrostatic test loads by 5.6.3 or 5.6.4.

b) The thickness of all shell courses shall be that determined from an elastic analysis per 5.6.5 using final plate thicknesses.

The inside of an upper shell course shall not project beyond the inside surface of the shell course below (except within tolerances provided in 7.2.3.2).

5.6.1.4 The tank shell shall be checked for stability against buckling from the design wind speed in accordance with 5.9.6. If required for stability, intermediate girders, increased shell-plate thicknesses, or both shall be used.

5.6.1.5 Isolated radial loads on the tank shell, such as those caused by heavy loads on platforms and elevated walkways between tanks, shall be distributed by rolled structural sections, plate ribs, or built-up members.

5.6.2 Allowable Stress

5.6.2.1 The maximum allowable product design stress, S_d, shall be as shown in Table 5.2a and Table 5.2b. The corroded plate thicknesses shall be used in the calculation. The design stress basis, S_d, shall be either two-thirds the yield strength or two-fifths the tensile strength, whichever is less.

5.6.2.2 The maximum allowable hydrostatic test stress, S_t, shall be as shown in Table 5.2a and Table 5.2b. The nominal plate thicknesses shall be used in the calculation. The hydrostatic test basis shall be either three-fourths the yield strength or three-sevenths the tensile strength, whichever is less.

Table 5.2a—Permissible Plate Materials and Allowable Stresses (SI)

Plate Specification	Grade	Nominal Plate Thickness t mm	Minimum Yield Strength MPa	Minimum Tensile Strength MPa	Product Design Stress S_d MPa	Hydrostatic Test Stress S_t MPa
ASTM Specifications						
A283M	C		205	380	137	154
A285M	C		205	380	137	154
A131M	A, B		235	400	157	171
A36M	—		250	400	160	171
A131M	EH 36		360	490[a]	196	210
A573M	400		220	400	147	165
A573M	450		240	450	160	180
A573M	485		290	485[a]	193	208
A516M	380		205	380	137	154
A516M	415		220	415	147	165
A516M	450		240	450	160	180
A516M	485		260	485	173	195
A662M	B		275	450	180	193

Table 5.2a—Permissible Plate Materials and Allowable Stresses (SI) (Continued)

Plate Specification	Grade	Nominal Plate Thickness t mm	Minimum Yield Strength MPa	Minimum Tensile Strength MPa	Product Design Stress S_d MPa	Hydrostatic Test Stress S_t MPa
A662M	C		295	485[a]	194	208
A537M	1	$t \leq 65$ $65 < t \leq 100$	345 310	485[a] 450[b]	194 180	208 193
A537M	2	$t \leq 65$ $65 < t \leq 100$	415 380	550[a] 515[b]	220 206	236 221
A633M	C, D	$t \leq 65$ $65 < t \leq 100$	345 315	485[a] 450[b]	194 180	208 193
A737M	B		345	485[a]	194	208
A841M	Class 1, Grades A and B		345	485[a]	194	208
A841M	Class 2, Grades A and B		415	550[a]	220	236
CSA Specifications						
G40.21M	260W		260	410	164	176
G40.21M	260 WT		260	410	164	176
G40.21M	300W		300	440	176	189
G40.21M	300WT		300	440	176	189
G40.21M	350W		350	450	180	193
G40.21M	350WT	$t \leq 65$ $65 < t \leq 100$	350 320	450[a] 450[a]	180 180	193 193
National Standards						
	235		235	365	137	154
	250		250	400	157	171
	275		275	430	167	184

Table 5.2a—Permissible Plate Materials and Allowable Stresses (SI) (Continued)

Plate Specification	Grade	Nominal Plate Thickness t mm	Minimum Yield Strength MPa	Minimum Tensile Strength MPa	Product Design Stress S_d MPa	Hydrostatic Test Stress S_t MPa
ISO Specifications						
ISO 630	S275C, D	$t \leq 16$	275	410	164	176
		$16 < t \leq 40$	265	410	164	176
	S355C, D	$t \leq 16$	355	470[a]	188	201
		$16 < t \leq 40$	345	470[a]	188	201
		$40 < t \leq 50$	335	470[a]	188	201
EN Specifications						
EN 10025	S 275J0, J2	$t \leq 16$	275	410	164	176
		$16 < t \leq 40$	265	410	164	176
	S 355J0, J2, K2	$t \leq 16$	355	470[a]	188	201
		$16 < t \leq 40$	345	470[a]	188	201
		$40 < t \leq 50$	335	470[a]	188	201

● [a] By agreement between the Purchaser and the Manufacturer, the tensile strength of ASTM A537M, Class 2, and A841M, Class 2 materials may be increased to 585 MPa minimum and 690 MPa maximum. The tensile strength of the other listed materials may be increased to 515 MPa minimum and 620 MPa maximum. When this is done, the allowable stresses shall be determined as stated in 5.6.2.1 and 5.6.2.2.

● [b] By agreement between the Purchaser and the Manufacturer, the tensile strength of ASTM A537M, Class 2 materials may be increased to 550 MPa minimum and 690 MPa maximum. The tensile strength of the other listed materials may be increased to 485 MPa minimum and 620 MPa maximum. When this is done, the allowable stresses shall be determined as stated in 5.6.2.1 and 5.6.2.2.

5.6.2.3 Annex A permits an alternative shell design with a fixed allowable stress of 145 MPa (21,000 lbf/in.^{2}) and a joint efficiency factor of 0.85 or 0.70. This design may only be used for tanks with shell thicknesses less than or equal to 13 mm ($^1/_2$ in.).

5.6.2.4 Structural design stresses shall conform to the allowable working stresses given in 5.10.3.

5.6.3 Calculation of Thickness by the 1-Foot Method

5.6.3.1 The 1-foot method calculates the thicknesses required at design points 0.3 m (1 ft) above the bottom of each shell course. Annex A permits only this design method. This method shall not be used for tanks larger than 61 m (200 ft) in diameter.

● **5.6.3.2** The required minimum thickness of shell plates shall be the greater of the values computed by the following formulas:

In SI units:

$$t_d = \frac{4.9D(H-0.3)G}{S_d} + CA$$

$$t_t = \frac{4.9D(H-0.3)}{S_t}$$

Table 5.2b—Permissible Plate Materials and Allowable Stresses (USC)

Plate Specification	Grade	Nominal Plate Thickness t in.	Minimum Yield Strength psi	Minimum Tensile Strength psi	Product Design Stress S_d psi	Hydrostatic Test Stress S_t psi
ASTM Specifications						
A283	C		30,000	55,000	20,000	22,500
A285	C		30,000	55,000	20,000	22,500
A131	A, B		34,000	58,000	22,700	24,900
A36	—		36,000	58,000	23,200	24,900
A131	EH 36		51,000	71,000[a]	28,400	30,400
A573	58		32,000	58,000	21,300	24,000
A573	65		35,000	65,000	23,300	26,300
A573	70		42,000	70,000[a]	28,000	30,000
A516	55		30,000	55,000	20,000	22,500
A516	60		32,000	60,000	21,300	24,000
A516	65		35,000	65,000	23,300	26,300
A516	70		38,000	70,000	25,300	28,500
A662	B		40,000	65,000	26,000	27,900
A662	C		43,000	70,000[a]	28,000	30,000
A537	1	$t \leq 2^1/_2$ $2^1/_2 < t \leq 4$	50,000 45,000	70,000[a] 65,000[b]	28,000 26,000	30,000 27,900
A537	2	$t \leq 2^1/_2$ $2^1/_2 < t \leq 4$	60,000 55,000	80,000[a] 75,000[b]	32,000 30,000	34,300 32,100
A633	C, D	$t \leq 2^1/_2$ $2^1/_2 < t \leq 4$	50,000 46.000	70,000[a] 65,000[b]	28,000 26,000	30,000 27,900
A737	B		50,000	70,000[a]	28,000	30,000
A841	Class 1, Grades A and B		50,000	70,000[a]	28,000	30,000
A841	Class 2, Grades A and B		60,000	80,000[a]	32,000	34,300
CSA Specifications						
G40.21	38W		38,000	60,000	24,000	25,700
G40.21	38WT		38,000	60,000	24,000	25,700

Table 5.2b—Permissible Plate Materials and Allowable Stresses (USC) (Continued)

Plate Specification	Grade	Nominal Plate Thickness t in.	Minimum Yield Strength psi	Minimum Tensile Strength psi	Product Design Stress S_d psi	Hydrostatic Test Stress S_t psi
G40.21	44W		44,000	64,000	25,600	27,400
G40.21	44WT		44,000	64,000	25,600	27,400
G40.21	50W		50,000	65,000	26,000	27,900
G40.21	50WT	$t \leq 2^1/2$	50,000	65,000[a]	26,000	27,900
		$2^1/2 < t \leq 4$	46,000	65,000[a]	26,000	27,900
National Standards						
	235		34,000	52,600	20,000	22,500
	250		36,000	58,300	22,700	25,000
	275		40,000	62,600	24,000	26,800
ISO Specifications						
ISO 630	S275C, D	$t \leq 5/8$	39,900	59,500	23,800	25,500
		$5/8 < t \leq 1^1/2$	38,400	59,500	23,800	25,500
	S355C, D	$t \leq 5/8$	51,500	68,100[a]	27,200	29,200
		$5/8 < t \leq 1^1/2$	50,000	68,100[a]	27,200	29,200
		$1^1/2 < t \leq 2$	48,600	68,100[a]	27,200	29,200
EN Specifications						
EN 10025	S 275J0, J2	$t \leq 5/8$	39,900	59,500	23,800	25,500
		$5/8 < t \leq 1^1/2$	38,400	59,500	23,800	25,500
	S 355J0, J2, K2	$t \leq 5/8$	51,500	68,100[a]	27,200	29,200
		$5/8 < t \leq 1^1/2$	50,000	68,100[a]	27,200	29,200
		$1^1/2 < t \leq 2$	48,600	68,100[a]	27,200	29,200

• [a] By agreement between the Purchaser and the Manufacturer, the tensile strength of ASTM A537M, Class 2, and A841M, Class 2 materials may be increased to 85,000 psi minimum and 100,000 psi maximum. The tensile strength of the other listed materials may be increased to 75,000 psi minimum and 90,000 psi maximum. When this is done, the allowable stresses shall be determined as stated in 5.6.2.1 and 5.6.2.2.

• [b] By agreement between the Purchaser and the Manufacturer, the tensile strength of ASTM A537M, Class 2 materials may be increased to 80,000 psi minimum and 100,000 psi maximum. The tensile strength of the other listed materials may be increased to 70,000 psi minimum and 90,000 psi maximum. When this is done, the allowable stresses shall be determined as stated in 5.6.2.1 and 5.6.2.2.

where

t_d is the design shell thickness, in mm;

t_t is the hydrostatic test shell thickness, in mm;

D is the nominal tank diameter, in m (see 5.6.1.1, Note 1);

● H is the design liquid level, in m:

is the height from the bottom of the course under consideration to the top of the shell including the top angle, if any; to the bottom of any overflow that limits the tank filling height; or to any other level specified by the Purchaser, restricted by an internal floating roof, or controlled to allow for seismic wave action;

● G is the design specific gravity of the liquid to be stored, as specified by the Purchaser;

● CA is the corrosion allowance, in mm, as specified by the Purchaser (see 5.3.2);

S_d is the allowable stress for the design condition, in MPa (see 5.6.2.1);

S_t is the allowable stress for the hydrostatic test condition, in MPa (see 5.6.2.2).

In USC units:

$$t_d = \frac{2.6D(H-1)G}{S_d} + CA$$

$$t_t = \frac{2.6D(H-1)}{S_t}$$

where

t_d is the design shell thickness, in inches;

t_t is the hydrostatic test shell thickness, in inches;

D is the nominal tank diameter, in ft (see 5.6.1.1, Note 1);

● H is the design liquid level, in ft:

is the height from the bottom of the course under consideration to the top of the shell including the top angle, if any; to the bottom of any overflow that limits the tank filling height; or to any other level specified by the Purchaser, restricted by an internal floating roof, or controlled to allow for seismic wave action;

● G is the design specific gravity of the liquid to be stored, as specified by the Purchaser;

● CA is the corrosion allowance, in inches, as specified by the Purchaser (see 5.3.2);

S_d is the allowable stress for the design condition, in lbf/in.^{2} (see 5.6.2.1);

S_t is the allowable stress for the hydrostatic test condition, in lbf/in.^{2} (see 5.6.2.2).

5.6.4 Calculation of Thickness by the Variable-Design-Point Method

NOTE This procedure normally provides a reduction in shell-course thicknesses and total material weight, but more important is its potential to permit construction of larger diameter tanks within the maximum plate thickness limitation. For background information, see L.P. Zick and R.V. McGrath, "Design of Large Diameter Cylindrical Shells."[15]

● **5.6.4.1** Design by the variable-design-point method gives shell thicknesses at design points that result in the calculated stresses being relatively close to the actual circumferential shell stresses. This method may only be used when the Purchaser has not specified that the 1-foot method be used and when the following is true:

In SI units:

$$\frac{L}{H} \le \frac{1000}{6}$$

where

L equals $(500\ Dt)^{0.5}$, in mm;

D is the tank diameter, in m;

t is the bottom-course corroded shell thickness, in mm;

H is the maximum design liquid level (see 5.6.3.2), in m.

In USC units:

$$\frac{L}{H} \le 2$$

where

L equals $(6\ Dt)^{0.5}$, in inches;

D is the tank diameter, in ft;

t is the bottom-course corroded shell thickness, in inches;

H is the maximum design liquid level (see 5.6.3.2), in ft.

5.6.4.2 The minimum plate thicknesses for both the design condition and the hydrostatic test condition shall be determined as outlined. Complete, independent calculations shall be made for all of the courses for the design condition and for the hydrostatic test condition. The required shell thickness for each course shall be the greater of the design shell thickness plus any corrosion allowance or the hydrostatic test shell thickness, but the total shell thickness shall not be less than the shell thickness required by 5.6.1.1, 5.6.1.3, and 5.6.1.4. When a greater thickness is used for a shell course, the greater thickness may be used for subsequent calculations of the thicknesses of the shell courses above the course that has the greater thickness, provided the greater thickness is shown as the required design thickness on the Manufacturer's drawing (see W.3).

5.6.4.3 To calculate the bottom-course thicknesses, preliminary values t_{pd} and t_{pt} for the design and hydrostatic test conditions shall first be calculated from the formulas in 5.6.3.2.

5.6.4.4 The bottom-course thicknesses t_{1d} and t_{1t} for the design and hydrostatic test conditions shall be calculated using the following formulas:

[15] L.P. Zick and R.V. McGrath, "Design of Large Diameter Cylindrical Shells," *Proceedings*—Division of Refining, American Petroleum Institute, New York, 1968, Volume 48, pp. 1114 – 1140.

In SI units:

$$t_{1d} = \left(1.06 - \frac{0.0696D}{H}\sqrt{\frac{HG}{S_d}}\right)\left(\frac{4.9HDG}{S_d}\right) + CA$$

In USC units:

$$t_{1d} = \left(1.06 - \frac{0.463D}{H}\sqrt{\frac{HG}{S_d}}\right)\left(\frac{2.6HDG}{S_d}\right) + CA$$

NOTE For the design condition, t_{1d} need not be greater than t_{pd}.

In SI units:

$$t_{1t} = \left(1.06 - \frac{0.0696D}{H}\sqrt{\frac{H}{S_t}}\right)\left(\frac{4.9HD}{S_t}\right)$$

In USC units:

$$t_{1t} = \left(1.06 - \frac{0.463D}{H}\sqrt{\frac{H}{S_t}}\right)\left(\frac{2.6HD}{S_t}\right)$$

NOTE For the hydrostatic test condition, t_{1t} need not be greater than t_{pt}.

5.6.4.5 To calculate the second-course thicknesses for both the design condition and the hydrostatic test condition, the value of the following ratio shall be calculated for the bottom course:

$$\frac{h_1}{(rt_1)^{0.5}}$$

where

h_1 is the height of the bottom shell course, in mm (in.);

r is the nominal tank radius, in mm (in.);

t_1 is the calculated corroded thickness of the bottom shell course, in mm (in.), used to calculate t_2 (design). The calculated hydrostatic thickness of the bottom shell course shall be used to calculate t_2 (hydrostatic test).

If the value of the ratio is less than or equal to 1.375:

$$t_2 = t_1$$

If the value of the ratio is greater than or equal to 2.625:

$$t_2 = t_{2a}$$

If the value of the ratio is greater than 1.375 but less than 2.625:

$$t_2 = t_{2a} + (t_1 - t_{2a})\left[2.1 - \frac{h_1}{1.25(rt_1)^{0.5}}\right]$$

where

t_2 is the minimum design thickness of the second shell course, in mm (in.);

t_{2a} is the corroded thickness of the second shell course, in mm (in.), as calculated for an upper shell course as described in 5.6.4.6, 5.6.4.7, and 5.6.4.8. In calculating second shell course thickness (t_2) for design case and hydrostatic test case, applicable values of t_{2a} and t_1 shall be used.

The preceding formula for t_2 is based on the same allowable stress being used for the design of the bottom and second courses. For tanks where the value of the ratio is greater than or equal to 2.625, the allowable stress for the second course may be lower than the allowable stress for the bottom course when the methods described in 5.6.4.6 through 5.6.4.8 are used.

5.6.4.6 To calculate the upper-course thicknesses for both the design condition and the hydrostatic test condition, a preliminary value t_u for the upper-course corroded thickness shall be calculated using the formulas in 5.6.3.2, and then the distance x of the variable design point from the bottom of the course shall be calculated using the lowest value obtained from the following:

In SI units:

$$x_1 = 0.61\,(rt_u)^{0.5} + 320\,CH$$

$$x_2 = 1000\,CH$$

$$x_3 = 1.22\,(rt_u)^{0.5}$$

where

t_u is the corroded thickness of the upper course at the girth joint, in mm;

C equals $[K^{0.5}(K-1)]/(1+K^{1.5})$;

K equals t_L / t_u;

t_L is the corroded thickness of the lower course at the girth joint, in mm;

• H is the design liquid level (see 5.6.3.2), in m.

In USC units:

$$x_1 = 0.61\,(rt_u)^{0.5} + 3.84\,CH$$

$$x_2 = 12\,CH$$

$$x_3 = 1.22\,(rt_u)^{0.5}$$

where

t_u is the corroded thickness of the upper course at the girth joint, in inches;

C equals $[K^{0.5}(K-1)]/(1+K^{1.5})$;

K equals t_L / t_u;

t_L is the corroded thickness of the lower course at the girth joint, in inches;

● H is the design liquid level (see 5.6.3.2), in ft.

5.6.4.7 The minimum thickness t_x for the upper shell courses shall be calculated for both the design condition (t_{dx}) and the hydrostatic test condition (t_{tx}) using the minimum value of *x* obtained from 5.6.4.6:

In SI units:

$$t_{dx} = \frac{4.9D\left(H - \frac{x}{1000}\right)G}{S_d} + CA$$

$$t_{tx} = \frac{4.9D\left(H - \frac{x}{1000}\right)}{S_t}$$

In USC units:

$$t_{dx} = \frac{2.6D\left(H - \frac{x}{12}\right)G}{S_d} + CA$$

$$t_{tx} = \frac{2.6D\left(H - \frac{x}{12}\right)}{S_t}$$

5.6.4.8 The steps described in 5.6.4.6 and 5.6.4.7 shall be repeated using the calculated value of t_x as t_u until there is little difference between the calculated values of t_x in succession (repeating the steps twice is normally sufficient). Repeating the steps provides a more exact location of the design point for the course under consideration and, consequently, a more accurate shell thickness.

5.6.4.9 There are two examples provided in Annex K. Example #1 are step-by-step calculations illustrating an application of the variable-design-point method to a tank with a diameter of 85 m (280 ft) and a height of 19.2 m (64 ft) to determine shell-plate thicknesses for the first three courses for the hydrostatic test condition only. Example #2 demonstrates the variable-design-point design method in US Customary units for a tank with a diameter of 280 ft and a height of 40 ft with varying corrosion allowances and varying materials for both the design and hydrostatic test conditions.

5.6.5 Calculation of Thickness by Elastic Analysis

For tanks where L/H is greater than 1000/6 (2 in USC units), the selection of shell thicknesses shall be based on an elastic analysis that shows the calculated circumferential shell stresses to be below the allowable stresses given in Table 5.2a and Table 5.2b. The boundary conditions for the analysis shall assume a fully plastic moment caused by yielding of the plate beneath the shell and zero radial growth.

5.7 Shell Openings

5.7.1 General

5.7.1.1 The following requirements for shell openings are intended to restrict the use of appurtenances to those providing for attachment to the shell by welding. See Figure 5.6.

5.7.1.2 The shell opening designs described in this standard are required, except for alternative designs allowed in 5.7.1.8.

5.7.1.3 Flush-type cleanout fittings and flush-type shell connections shall conform to the designs specified in 5.7.7 and 5.7.8.

• **5.7.1.4** When a size intermediate to the sizes listed in Tables 5.3a through 5.12b is specified by the Purchaser, the construction details and reinforcements shall conform to the next larger opening listed in the tables. The size of the opening or tank connection shall not be larger than the maximum size given in the appropriate table.

5.7.1.5 Openings near the bottom of a tank shell will tend to rotate with vertical bending of the shell under hydrostatic loading. Shell openings in this area that have attached piping or other external loads shall be reinforced not only for the static condition but also for any loads imposed on the shell connections by the restraint of the attached piping to the shell rotation. The external loads shall be minimized, or the shell connections shall be relocated outside the rotation area. Annex P provides a method for evaluating openings that conform to Table 5.6a and Table 5.6b.

5.7.1.6 Sheared or oxygen-cut surfaces on manhole necks, nozzle necks, reinforcing plates, and shell-plate openings shall be made uniform and smooth, with the corners rounded except where the surfaces are fully covered by attachment welds.

5.7.1.7 Shell openings may be reinforced by the use of an insert plate/reinforcing plate combination or thickened insert plate per Figure 5.7b. A rectangular insert plate or thickened insert plate shall have rounded corners (except for edges terminating at the tank bottom or at joints between shell courses) with a radius which is greater than or equal to the larger of 150 mm (6 in.) or $6t$ where t is the thickness of the shell course containing the insert plate or thickened insert plate. The insert plate or thickened insert plate may contain multiple shell openings. The thickness and dimensions of insert plate or thickened insert plate shall provide the reinforcing required per 5.7.2. The weld spacing shall meet the requirements of 5.7.3. The periphery of thickened insert plates shall have a 1:4 tapered transition to the thickness of the adjoining shell material when the insert plate thickness exceeds the adjacent shell thickness by more than 3 mm ($^1/_8$ in.).

• **5.7.1.8** The shape and dimensions of the shell opening reinforcement, illustrated in Figure 5.7a, Figure 5.7b,and Figure 5.8 and dimensioned in the related tables may be altered as long as the reinforcement meets the area, welding, and weld spacing requirements outlined in 5.7.2 and 5.7.3. For reinforcing plates greater than $^1/_2$ in. thick, with approval of the Purchaser, reinforcement and welding (excluding weld spacing) of shell openings that comply with API 620, Section 5 are acceptable. These statements of permissible alternatives of shell opening reinforcement and welding do not apply to flush-type cleanout fittings, flush-type shell connections or similar configurations.