

**Date of Issue:** July 2013

**Affected Publication:** API Standard 650, *Welded Tanks for Oil Storage*, Twelfth Edition, March 2013

## **ERRATA**

*This errata corrects editorial errors in the twelfth edition of API Standard 650.*

*Replace the following pages with the attached:*

4-7

4-8

4-9

5-16

5-34

5-35

5-61

5-87

8-7

C-2

F-3

F-4

M-2

P-5

S-7

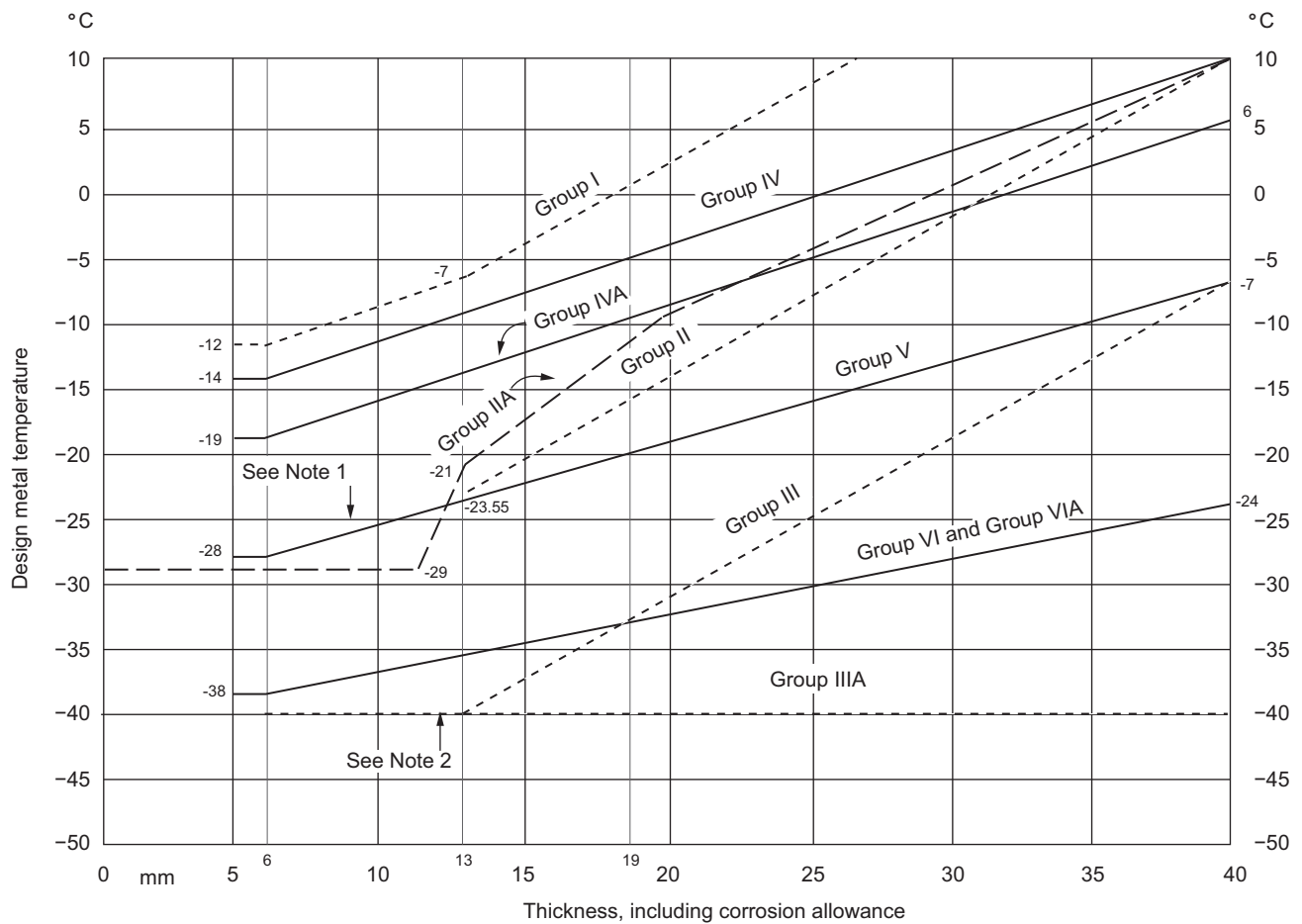
V-2

V-8

V-11

V-23

X-5



NOTE 1 The Group II and Group V lines coincide at thicknesses less than 13 mm.

NOTE 2 The Group III and Group IIIA lines coincide at thicknesses less than 13 mm.

NOTE 3 The materials in each group are listed in Table 4.4a and Table 4.4b.

NOTE 4 **Deleted.**

NOTE 5 Use the Group IIA and Group VIA curves for pipe and flanges (see 4.5.4.2 and 4.5.4.3).

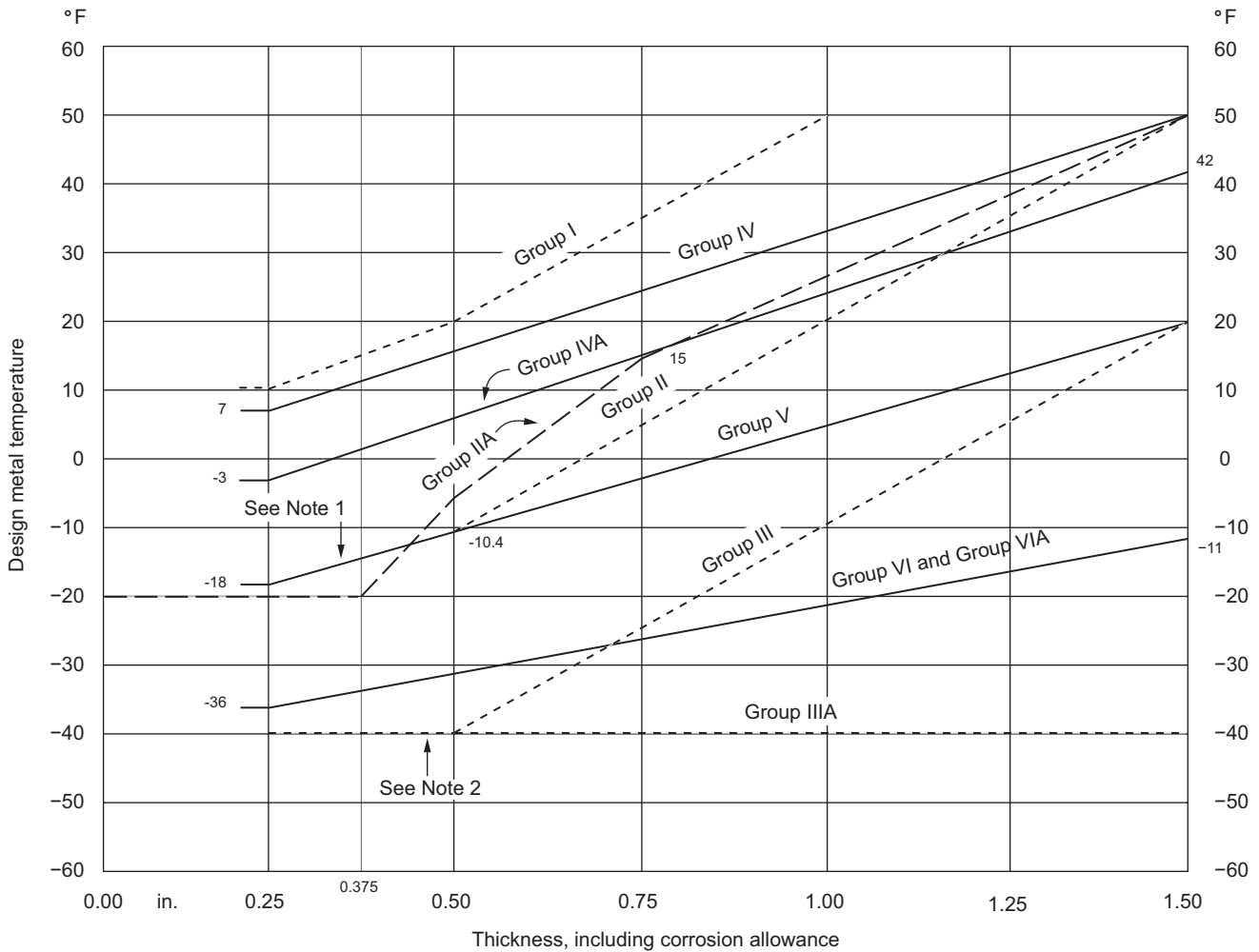
NOTE 6 Linear equations provided in Table 4.3a can be used to calculate Design Metal Temperature (DMT) for each API material group and the thickness range.

**Figure 4.1a—Minimum Permissible Design Metal Temperature for Materials Used in Tank Shells without Impact Testing (SI)**

(normalized, normalized and tempered, or quenched and tempered), notch toughness shall be demonstrated on each plate as heat treated when 4.2.11.2 requirements are specified. Isothermal lines of lowest one-day mean temperature are shown in Figure 4.2.

**4.2.10.4** Plate used to reinforce shell openings and insert plates shall be of the same material as the shell plate to which they are attached or shall be of any appropriate material listed in Table 4.4a, Table 4.4b, Figure 4.1a, and Figure 4.1b. Except for nozzle and manway necks, the material shall be of equal or greater yield and tensile strength and shall be compatible with the adjacent shell material (see 4.2.10.1 and 5.7.2.3, Item d).

**4.2.10.5** The requirements in 4.2.10.4 apply only to shell nozzles and manholes. Materials for roof nozzles and manholes do not require special toughness.



- NOTE 1 The Group II and Group V lines coincide at thicknesses less than 1/2 in.
- NOTE 2 The Group III and Group IIIA lines coincide at thicknesses less than 1/2 in.
- NOTE 3 The materials in each group are listed in Table 4.4a and Table 4.4b.
- NOTE 4 Deleted.
- NOTE 5 Use the Group IIA and Group VIA curves for pipe and flanges (see 4.5.4.2 and 4.5.4.3).
- NOTE 6 Linear equations provided in Table 4.3b can be used to calculate Design Metal Temperature (DMT) for each API material group and the thickness range.

**Figure 4.1b—Minimum Permissible Design Metal Temperature for Materials Used in Tank Shells without Impact Testing (USC)**

**4.2.11 Toughness Procedure**

**4.2.11.1** When a material’s toughness must be determined, it shall be done by one of the procedures described in 4.2.11.2, 4.2.11.3, and 4.2.11.4, as specified in 4.2.10.

**4.2.11.2** Each plate as rolled or heat treated shall be impact tested in accordance with 4.2.9 at or below the design metal temperature to show Charpy V-notch longitudinal (or transverse) values that fulfill the minimum requirements of Table 4.5a and Table 4.5b (see 4.2.9 for the minimum values for one specimen and for subsized specimens). As used here, the term plate as rolled refers to the unit plate rolled from a slab or directly from an ingot in its relation to the location and number of specimens, not to the condition of the plate.

Table 4.3a—Linear Equations for Figure 4.1a (SI)

API Group #	Thickness Range	Equation
I	$6 \leq X < 13$	$Y = 0.714X - 16.286$
I	$13 \leq X \leq 25$	$Y = 1.417X - 25.417$
II	$6 \leq X < 13$	$Y = 0.634X - 31.81$
II	$13 \leq X \leq 40$	$Y = 1.243X - 39.72$
IIA	$10 \leq X < 13$	$Y = 2.667X - 55.667$
IIA	$13 \leq X \leq 19$	$Y = 2X - 47$
IIA	$19 \leq X \leq 40$	$Y = 0.905X - 26.19$
III	$6 \leq X \leq 13$	$Y = -40$
III	$13 \leq X \leq 40$	$Y = 1.222X - 55.89$
IIIA	$6 \leq X \leq 40$	$Y = -40$
IV	$6 \leq X \leq 40$	$Y = 0.7059X - 18.235$
IVA	$6 \leq X \leq 40$	$Y = 0.7353X - 23.412$
V	$6 \leq X \leq 40$	$Y = 0.6176X - 31.71$
VI, VIA	$6 \leq X \leq 40$	$Y = 0.4112X - 40.471$
Y = Design Metal Temperature (°C)		
X = Thickness including corrosion (mm)		

Table 4.3b—Linear Equations for Figure 4.1b (USC)

API Group #	Thickness Range	Equation
I	$0.25 \leq X < 0.5$	$Y = 40X$
I	$0.5 \leq X \leq 1.0$	$Y = 60X - 10$
II	$0.25 \leq X < 0.5$	$Y = 30.4X - 25.6$
II	$0.5 \leq X \leq 1.5$	$Y = 60.4X - 40.6$
IIA	$0.375 \leq X < 0.5$	$Y = 120X - 65$
IIA	$0.5 \leq X \leq 0.75$	$Y = 80X - 45$
IIA	$0.75 \leq X \leq 1.5$	$Y = 46.667X - 20$
III	$0.25 \leq X \leq 0.5$	$Y = -40$
III	$0.5 \leq X \leq 1.5$	$Y = 60X - 70$
IIIA	$0.25 \leq X \leq 1.5$	$Y = -40$
IV	$0.25 \leq X \leq 1.5$	$Y = 34.4X - 1.6$
IVA	$0.25 \leq X \leq 1.5$	$Y = 36X - 12$
V	$0.25 \leq X \leq 1.5$	$Y = 30.4X - 25.6$
VI, VIA	$0.25 \leq X \leq 1.5$	$Y = 20X - 41$
Y = Design Metal Temperature (°F)		
X = Thickness including corrosion (in.)		

**4.2.11.3** For plate in the as-rolled condition, the thickest plate from each heat shall be impact tested. For TMCP material, each plate-as-rolled shall be impact tested. Impact testing shall be in accordance with 4.2.9 and shall fulfill the impact requirements of 4.2.11.2 at the design metal temperature.

- **4.2.11.4** The Manufacturer shall submit to the Purchaser test data for plates of the material demonstrating that based on past production from the same mill, the material has provided the required toughness at the design metal temperature.

### 4.3 Sheets

Sheets for fixed and floating roofs shall conform to ASTM A1011M, Grade 33. They shall be made by the open-hearth or basic oxygen process. Copper-bearing steel shall be used if specified on the purchase order. Sheets may be ordered on either a weight or a thickness basis, at the option of the tank Manufacturer.

### 4.4 Structural Shapes

**4.4.1** Structural steel shall conform to one of the following:

- ASTM A36M/A36.
- ASTM A131M/A131.
- ASTM A992M/A992.

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

Plate Thickness <sup>a</sup> of First Shell Course (mm)	Stress <sup>b</sup> 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

<sup>a</sup> Plate thickness refers to the corroded shell plate thickness for product design and nominal thickness for hydrostatic test design.

<sup>b</sup> 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 =  $((t_d - CA) / \text{corroded } t) (S_d)$   
Hydrostatic Test Stress =  $(t_t / \text{nominal } t) (S_t)$

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.

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

Plate Thickness <sup>a</sup> of First Shell Course (in.)	Stress <sup>b</sup> in First Shell Course (lbf/in. <sup>2</sup> )			
	≤ 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

<sup>a</sup> Plate thickness refers to the corroded shell plate thickness for product design and nominal thickness for hydrostatic test design.

<sup>b</sup> 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:

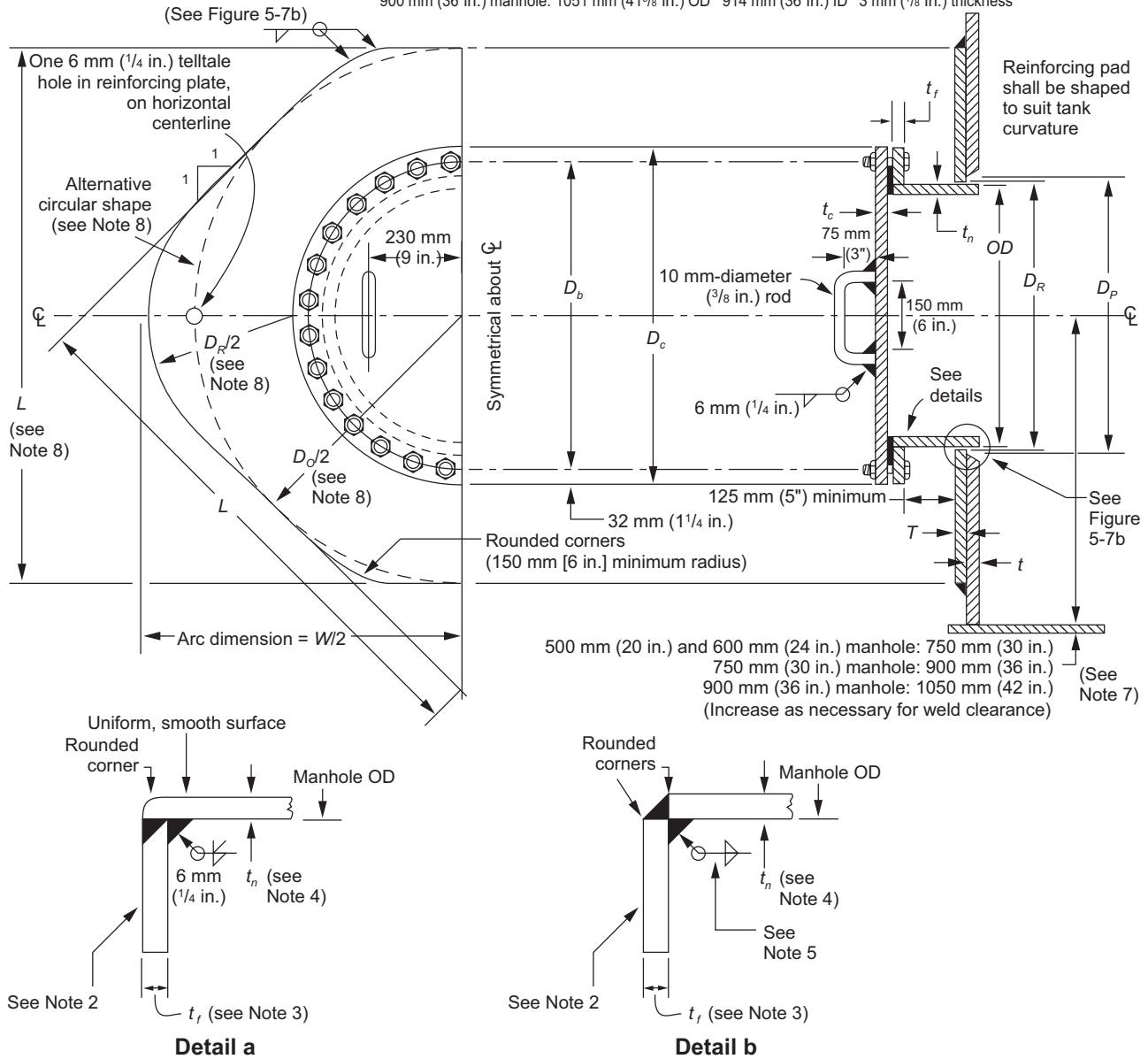
Product Stress =  $((t_d - CA) / \text{corroded } t) (S_d)$   
Hydrostatic Test Stress =  $(t_t / \text{nominal } t) (S_t)$

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.

500 mm (20 in.) and 600 mm (24 in.) shell manholes: twenty-eight 20 mm-diameter ( $\frac{3}{4}$  in.) bolts in 23 mm ( $\frac{7}{8}$  in.) holes  
 750 mm (30 in.) and 900 mm (36 in.) shell manholes: forty-two 20 mm-diameter ( $\frac{3}{4}$  in.) bolts in 23 mm ( $\frac{7}{8}$  in.) holes  
 (Bolt holes shall straddle the flange vertical centerline.)

Gasket (see Note 1):

- 500 mm (20 in.) manhole: 645 mm ( $25\frac{3}{8}$  in.) OD ' 508 mm (20 in.) ID ' 3 mm ( $\frac{1}{8}$  in.) thickness
- 600 mm (24 in.) manhole: 746 mm ( $29\frac{3}{8}$  in.) OD ' 610 mm (24 in.) ID ' 3 mm ( $\frac{1}{8}$  in.) thickness
- 750 mm (30 in.) manhole: 899 mm ( $35\frac{3}{8}$  in.) OD ' 762 mm (30 in.) ID ' 3 mm ( $\frac{1}{8}$  in.) thickness
- 900 mm (36 in.) manhole: 1051 mm ( $41\frac{3}{8}$  in.) OD ' 914 mm (36 in.) ID ' 3 mm ( $\frac{1}{8}$  in.) thickness



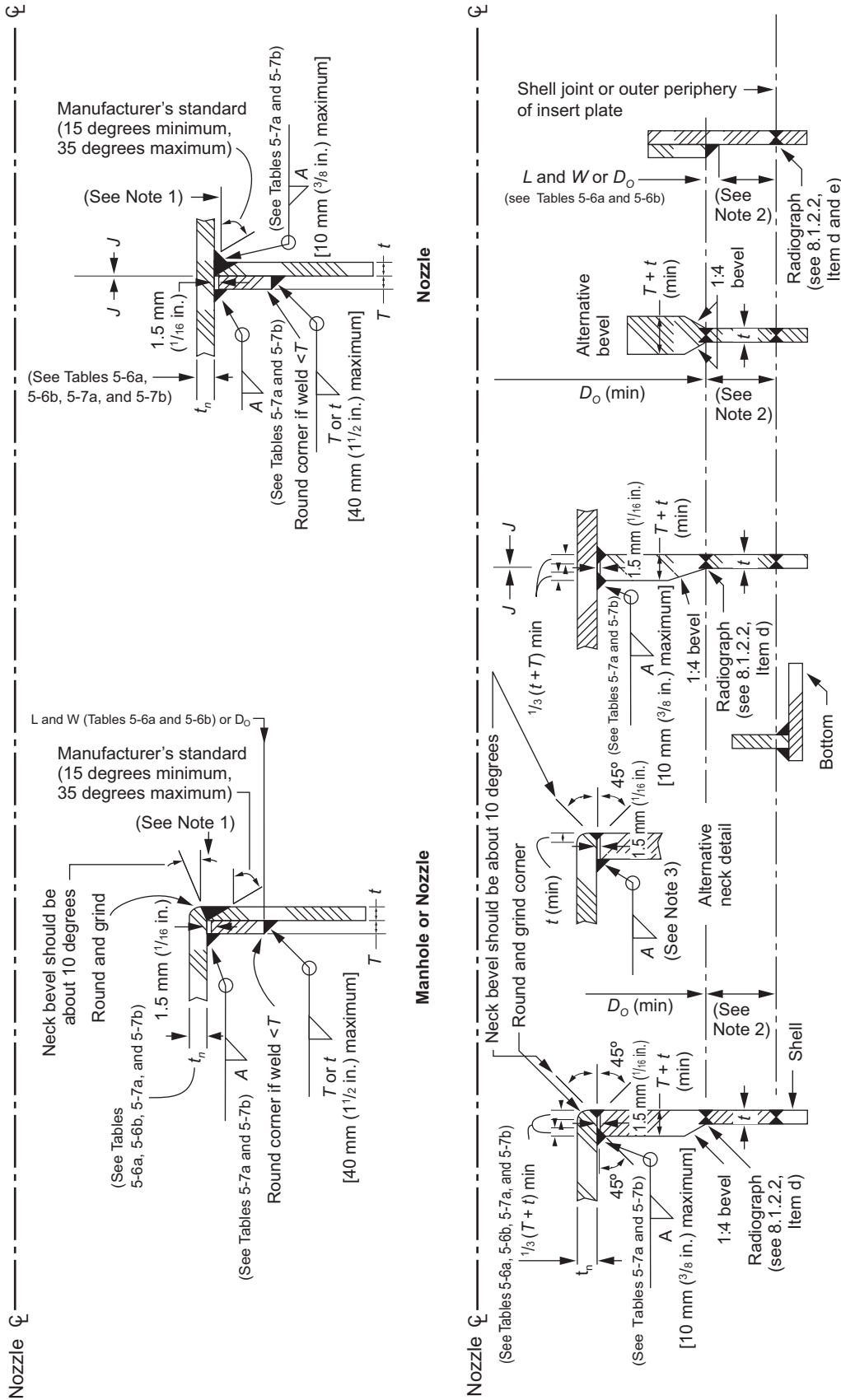
500 mm (20 in.) and 600 mm (24 in.) manhole: 750 mm (30 in.)  
 750 mm (30 in.) manhole: 900 mm (36 in.)  
 900 mm (36 in.) manhole: 1050 mm (42 in.)  
 (Increase as necessary for weld clearance)

NOTES

1. Gasket material shall be specified by the Purchaser. See 5.7.5.4.
2. The gasketed face shall be machine-finished to provide a minimum gasket-bearing width of 19 mm ( $\frac{3}{4}$  in.).
3. See Table 5.3a and Table 5.3b.
4. See Table 5.4a and Table 5.4b.
5. The size of the weld shall equal the thickness of the thinner member joined.
6. The shell nozzles shown in Figure 5.8 may be substituted for manholes.

7. The minimum centerline elevations allowed by Table 5.6a, Table 5.6b, and Figure 5.6 may be used when approved by the Purchaser.
8. For dimensions for OD, D<sub>R</sub>, D<sub>o</sub>, L, and W, see Table 5.6a and Table 5.6b, Columns 2, 4, 5, and 6. For Dimension D<sub>P</sub> see Table 5.7a and Table 5.7b, Column 3.
9. At the option of the Manufacturer, the manhole ID may be set to the OD dimension listed in Table 5.6a and Table 5.6b, Column 2. Reinforcement area and weld spacing must meet 5.7.2 and 5.7.3 requirements respectively.

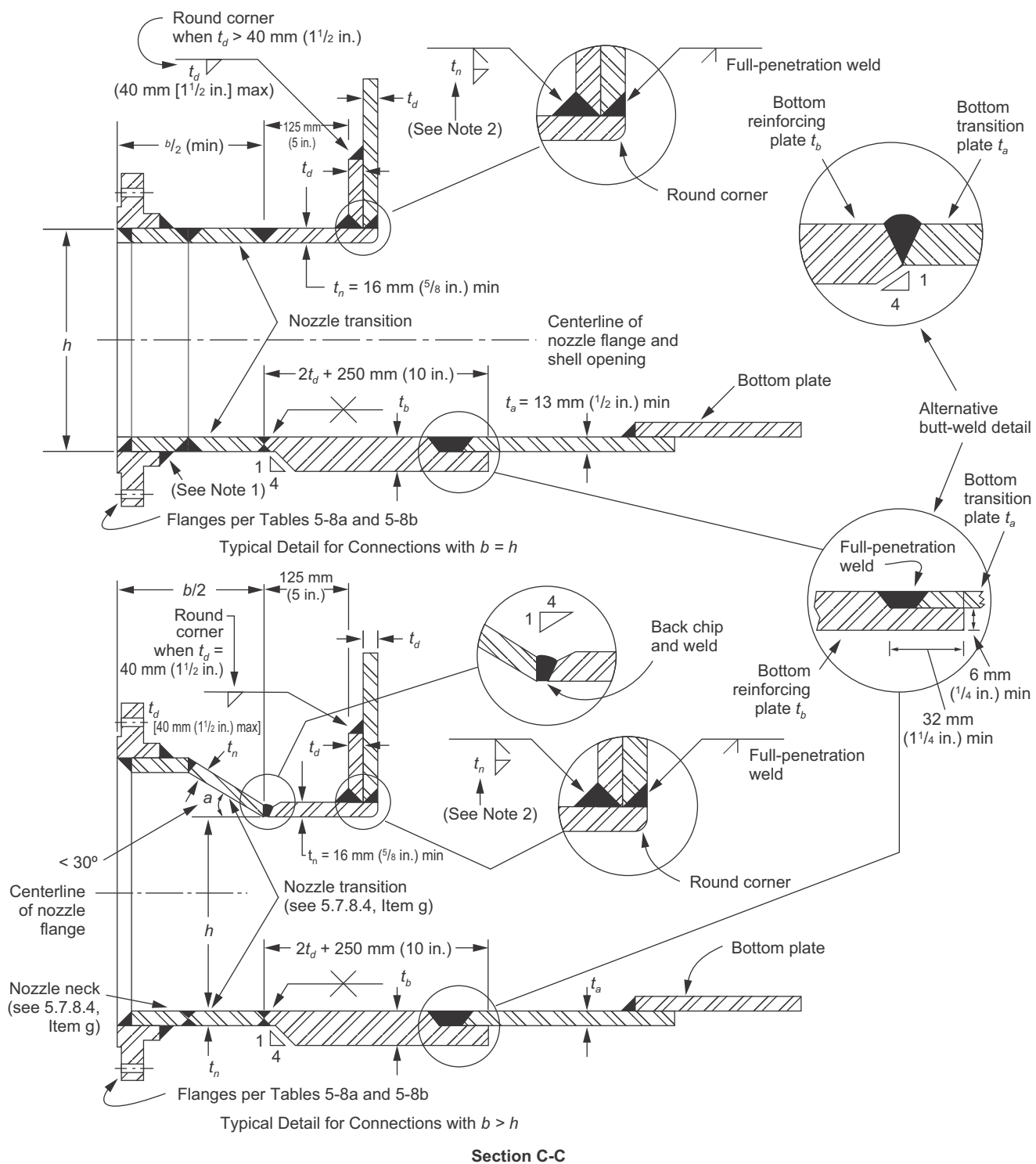
Figure 5.7a—Shell Manhole



**Insert-type Reinforcement for Manholes and Nozzles**

- Notes:
1. See Table 5.7a and Table 5.7b, Column 3, for the shell cutout, which shall not be less than the outside diameter of the neck plus 13 mm (1/2) in.
  2. See 5.7.3 for minimum spacing of welds at opening connections.
  3. The weld size shall be either A (from Table 5.7a and Table 5.7b, based on  $t$ ) or  $t_n$  (minimum neck thickness from Table 5.4a, Table 5.4b, Table 5.6a, Table 5.6b, Table 5.7a and Table 5.7b), whichever is greater.
  4. Other permissible insert details are shown in Figure 5.8 of API Standard 620. The reinforcement area shall conform to 5.7.2.
  5. Dimensions and weld sizes that are not shown are the same as those given in Figure 5.7a and Table 5.4a through Table 5.8b.
  6. Details of welding bevels may vary from those shown if agreed to by the Purchaser.

**Figure 5.7b—Details of Shell Manholes and Nozzles**



Note 1: Flange weld sizes shall be the smaller of the available hub material for  $t_n$ .

Note 2: Thickness of thinner plate joined 13 mm ( $\frac{1}{2}$  in.) maximum.

**Figure 5.14—Flush-type Shell Connection (Continued)**



In USC units:

$$t_b = \frac{h^2}{14,000} + \frac{b}{310} \sqrt{HG} + CA$$

where

$t_b$  is the minimum thickness of the bottom reinforcing plate, in inches;

$h$  is the vertical height of clear opening, in inches;

$b$  is the horizontal width of clear opening, in inches;

$H$  is the maximum design liquid level (see 5.6.3.2), in feet;

$G$  is the specific gravity, not less than 1.0.

The minimum value of  $t_b$  shall be:

16 mm ( $5/8$  in.) for  $HG \leq 14.4$  m (48 ft)

17 mm ( $11/16$  in.) for  $14.4$  m (48 ft)  $< HG \leq 16.8$  m (56 ft)

19 mm ( $3/4$  in.) for  $16.8$  m (56 ft)  $< HG \leq 19.2$  m (64 ft)

g) The corroded thickness of the nozzle neck and transition piece,  $t_n$ , shall be not less than 16 mm ( $5/8$  in.). External loads applied to the connection may require  $t_n$  to be greater than 16 mm ( $5/8$  in.).

**5.7.8.5** All materials in the flush-type shell connection assembly shall conform to the requirements in Section 4. The material of the shell plate in the connection assembly, the shell reinforcing plate, the nozzle neck attached to the shell, the transition piece, and the bottom reinforcing plate shall conform to 4.2.9 and Figure 4.1 for the respective thickness involved at the design metal temperature for the tank. The notch toughness of the bolting flange and the nozzle neck attached to the bolting flange shall be based on the governing thickness as defined in 4.5.5.3 and used in Figure 4.1. Additionally, the yield strength and the tensile strength of the shell plate at the flush-type shell connection and the shell reinforcing plate shall be equal to, or greater than, the yield strength and the tensile strength of the adjacent lowest shell course plate material.

**5.7.8.6** The nozzle transition between the flush connection in the shell and the circular pipe flange shall be designed in a manner consistent with the requirements of this standard. Where this standard does not cover all details of design and construction, the Manufacturer shall provide details of design and construction that will be as safe as the details provided by this standard.

**5.7.8.7** Where anchoring devices are required by Annex E and Annex F to resist shell uplift, the devices shall be spaced so that they will be located immediately adjacent to each side of the reinforcing plates around the opening.

**5.7.8.8** Adequate provision shall be made for free movement of connected piping to minimize thrusts and moments applied to the shell connection. Allowance shall be made for the rotation of the shell connection caused by the restraint of the tank bottom-to-shell expansion from stress and temperature as well as for the thermal and elastic movement of the piping. Rotation of the shell connection is shown in Figure 5.15.

**5.7.8.9** The foundation in the area of a flush-type connection shall be prepared to support the bottom reinforcing plate of the connection. The foundation for a tank resting on a concrete ringwall shall provide uniform support for both the bottom reinforcing plate and the remaining bottom plate under the tank shell. Different methods of supporting the bottom reinforcing plate under a flush-type connection are shown in Figure 5.13.

d) A **self-supporting umbrella roof** is a modified dome roof formed so that any horizontal section is a regular polygon with as many sides as there are roof plates that is supported only at its periphery.

## 5.10.2 General

**5.10.2.1 Loads:** All roofs and supporting structures shall be designed for load combinations (a), (b), (c), (e), (f), and (g).

- **5.10.2.2 Roof Plate Thickness:** Roof plates shall have a nominal thickness of not less than 5 mm (<sup>3</sup>/<sub>16</sub> in.) or 7-gauge sheet. Increased thickness may be required for supported cone roofs (see 5.10.4.4). Any required corrosion allowance for the plates of self-supporting roofs shall be added to the calculated thickness unless otherwise specified by the Purchaser. Any corrosion allowance for the plates of supported roofs shall be added to the greater of the calculated thickness or the minimum thickness or [5 mm (<sup>3</sup>/<sub>16</sub> in.) or 7-gauge sheet]. For frangible roof tanks, where a corrosion allowance is specified, the design must have frangible characteristics in the nominal (uncorroded) condition.

**5.10.2.3 Structural Member Attachment:** Roof plates of supported cone roofs shall not be attached to the supporting members unless otherwise approved by the Purchaser. Continuously attaching the roof to cone supporting members may be beneficial when interior lining systems are required, however, the tank roof cannot be considered frangible (see 5.10.2.6).

- **5.10.2.4 Structural Member Thickness:** All internal and external structural members shall have a minimum nominal thickness (new) of 4.3 mm (0.17 in.), and a minimum corroded thickness of 2.4 mm (0.094 in.), respectively, in any component, except that the minimum nominal thickness shall not be less than 6 mm (0.236 in.) for columns which by design normally resist axial compressive forces.

**5.10.2.5 Top Attachment:** Roof plates shall be attached to the top angle of the tank with a continuous fillet weld on the top side.

- **5.10.2.6 Frangible Roof:** A roof is considered frangible (see 5.8.5 for emergency venting requirement) if the roof-to-shell joint will fail prior to the shell-to-bottom joint in the event of excessive internal pressure. When a Purchaser specifies a tank with a frangible roof, the tank design shall comply with a, b, c, or d, of the following:

a) For tanks 15 m (50 ft) in diameter or greater, the tank shall meet all of the following.

- 1) The slope of the roof at the top angle attachment does not exceed 2:12.
- 2) The roof support members shall not be attached to the roof plate.
- 3) The roof is attached to the top angle with a single continuous fillet weld on the top side (only) that does not exceed 5 mm (<sup>3</sup>/<sub>16</sub> in.). No underside welding of roof to top angle (including seal welding) is permitted.
- 4) The roof-to-top angle compression ring is limited to details a through e in Figure F-2.
- 5) All members in the region of the roof-to-shell joint, including insulation rings, are considered as contributing to the roof-to-shell joint cross-sectional area (A) and this area is less than the limit shown below:

$$A = \frac{D_{LS}}{2\pi F_y \tan \theta}$$

NOTE The terms for this equation are defined in Annex F.

The top angle size required by 5.1.5.9.e may be reduced in size if required to meet the cross sectional area limit.

The reinforcement need not be removed except to the extent that it exceeds the maximum acceptable thickness or unless its removal is required by 8.1.3.4 for radiographic examination.

**8.5.3** A weld that fails to meet the criteria given in 8.5.1 shall be reworked before hydrostatic testing as follows:

- a) Any defects shall be removed by mechanical means or thermal gouging processes. Arc strikes discovered in or adjacent to welded joints shall be repaired by grinding and rewelding as required. Arc strikes repaired by welding shall be ground flush with the plate.
- b) Rewelding is required if the resulting thickness is less than the minimum required for design or hydrostatic test conditions. All defects in areas thicker than the minimum shall be feathered to at least a 4:1 taper.
- c) The repair weld shall be visually examined for defects.

**DELETED**

## **8.6 Vacuum Testing**

**8.6.1** Vacuum testing is performed using a testing box approximately 150 mm (6 in.) wide by 750 mm (30 in.) long with a clear window in the top, which provides proper visibility to view the area under examination. During testing, illumination shall be adequate for proper evaluation and interpretation of the test. The open bottom shall be sealed against the tank surface by a suitable gasket. Connections, valves, lighting and gauges, as required, shall be provided. A soap film solution or commercial leak detection solution, applicable to the conditions, shall be used.

**8.6.2** Vacuum testing shall be performed in accordance with a written procedure prepared by the Manufacturer of the tank. The procedure shall require:

- a) performing a visual examination of the bottom and welds prior to performing the vacuum-box test;
  - b) verifying the condition of the vacuum box and its gasket seals;
  - c) verifying that there is no quick bubble or spitting response to large leaks; and
  - d) applying the film solution to a dry area, such that the area is thoroughly wetted and a minimum generation of application bubbles occurs.
- **8.6.3** A partial vacuum of 21 kPa (3 lbf/in.<sup>2</sup>, 6 in. Hg) to 35 kPa (5 lbf/in.<sup>2</sup>, 10 in. Hg) gauge shall be used for the test. If specified by the Purchaser, a second partial vacuum test of 56 kPa (8 lbf/in.<sup>2</sup>, 16 in. Hg) to 70 kPa (10 lbf/in.<sup>2</sup>, 20 in. Hg) shall be performed for the detection of very small leaks.

**8.6.4** The Manufacturer shall determine that each vacuum-box operator meets the following requirements:

- a) has vision (with correction, if necessary) to be able to read a Jaeger Type 2 standard chart at a distance of not less than 300 mm (12 in.). Operators shall be checked annually to ensure that they meet this requirement; and
- b) is competent in the technique of the vacuum-box testing, including performing the examination and interpreting and evaluating the results; however, where the examination method consists of more than one operation, the operator performing only a portion of the test need only be qualified for that portion the operator performs.

**8.6.5** The vacuum-box test shall have at least 50 mm (2 in.) overlap of previously viewed surface on each application.

**8.6.6** The metal surface temperature limits shall be between 4 °C (40 °F) and 52 °C (125 °F), unless the film solution is proven to work at temperatures outside these limits, either by testing or Manufacturer's recommendations.

**8.6.7** A minimum light intensity of 1000 Lux (100 fc) at the point of examination is required during the application of the examination and evaluation for leaks.

**8.6.8** The vacuum shall be maintained for the greater of either at least 5 seconds or the time required to view the area under test.

**8.6.9** The presence of a through-thickness leak indicated by continuous formation or growth of a bubble(s) or foam, produced by air passing through the thickness, is unacceptable. The presence of a large opening leak, indicated by a quick bursting bubble or spitting response at the initial setting of the vacuum box is unacceptable. Leaks shall be repaired and retested.

- **8.6.10** A record or report of the test including a statement addressing temperature and light intensity shall be completed and furnished to the Purchaser upon request.
- **8.6.11** As an alternate to vacuum-box testing, a suitable tracer gas and compatible detector can be used to test the integrity of welded bottom joints for their entire length. Where tracer gas testing is employed as an alternate to vacuum-box testing, it shall meet the following requirements:
  - a) Tracer gas testing shall be performed in accordance with a written procedure which has been reviewed and approved by the Purchaser and which shall address as a minimum: the type of equipment used, surface cleanliness, type of tracer gas, test pressure, soil permeability, soil moisture content, satisfactory verification of the extent of tracer gas permeation, and the method or technique to be used including scanning rate and probe standoff distance.
  - b) The technique shall be capable of detecting leakage of  $1 \times 10^{-4}$  Pa m<sup>3</sup>/s ( $1 \times 10^{-3}$  std cm<sup>3</sup>/s) or smaller.
  - c) The test system parameters (detector, gas, and system pressure, i.e., level of pressure under bottom) shall be calibrated by placing the appropriate calibrated capillary leak, which will leak at a rate consistent with (b) above, in a temporary or permanent fitting in the tank bottom away from the tracer gas pressurizing point. Alternatively, by agreement between the Purchaser and the Manufacturer, the calibrated leak may be placed in a separate fitting pressurized in accordance with the system parameters.
  - d) While testing for leaks in the welded bottom joints, system parameters shall be unchanged from those used during calibration.

## **Annex C** (normative)

### **External Floating Roofs**

#### **• C.1 Scope**

**C.1.1** This Annex provides minimum requirements that, unless otherwise qualified in the text, apply to single-deck pontoon-type and double-deck-type floating roofs. See Section 3 for the definition of these roof types. This Annex is intended to limit only those factors that affect the safety and durability of the installation and that are considered to be consistent with the quality and safety requirements of this standard. Numerous alternative details and proprietary appurtenances are available; however, agreement between the Purchaser and the Manufacturer is required before they are used.

**C.1.2** The type of roof and seal to be provided shall be as specified on the Data Sheet, Line 30. If the type is not specified, the Manufacturer shall provide a roof and seal that is cost-effective and suitable for the specified service. Pan-type floating roofs shall not be used.

**C.1.3** The Purchaser is required to provide all applicable jurisdictional requirements that apply to external floating roofs (see 1.3).

**C.1.4** See Annex W for bid requirements pertaining to external floating roofs.

#### **C.2 Material**

The material requirements of Section 4 shall apply unless otherwise stated in this Annex. Castings shall conform to any of the following specifications:

- a) ASTM A27M, grade 405-205 (ASTM A27, grade 60-30), fully annealed;
- b) ASTM A27M, grade 450-240 (ASTM A27, grade 65-35), fully annealed or normalized and tempered, or quenched and tempered;
- c) ASTM A216M (ASTM A216) WCA, WCB, or WCC grades annealed and normalized, or normalized and tempered.

#### **C.3 Design**

##### **C.3.1 General**

- **C.3.1.1** The roof and accessories shall be designed and constructed so that the roof is allowed to float to the maximum design liquid level and then return to a liquid level that floats the roof well below the top of the tank shell without damage to any part of the roof, tank, or appurtenances. During such an occurrence, no manual attention shall be required to protect the roof, tank, or appurtenances. If a windskirt or top-shell extension is used, it shall contain the roof seals at the highest point of travel. The Purchaser shall provide appropriate alarm devices to indicate a rise of the liquid in the tank to a level above the normal and overflow protection levels (see NFPA 30 and API 2350). Overflow slots shall not be used as a primary means of detecting an overflow incident. If specified by the Purchaser (Table 4 of the Data Sheet), emergency overflow openings may be provided to protect the tank and floating roof from damage.
- **C.3.1.2** The application of corrosion allowances shall be a matter of agreement between the Purchaser and the Manufacturer. Corrosion allowance shall be added to the required minimum thickness or, when no minimum thickness is required, added to the minimum thickness required for functionality.

**C.3.1.3** Sleeves and fittings that penetrate the single deck or lower decks of annular pontoons or lower decks of double-deck roofs, except for automatic bleeder vents, rim space vents, and leg sleeves, shall have a minimum wall thickness of "Standard Wall" for pipe NPS 6 and larger and 6 mm ( $1/4$  in.) for all other pipe and plate construction unless otherwise specified on the Data Sheet, Table 5. Such penetrations shall extend into the liquid.

**C.3.1.4** The annular space between the roof outer rim of the floating roof and the product side of the tank shell shall be designed for proper clearance of the peripheral seal (see C.3.13). All appurtenances and internal components of the tank shall have adequate clearance for the proper operation of the completed roof assembly.

- **C.3.1.5** For tanks greater than 60 m (200 ft) in diameter, the deck portion of single-deck pontoon floating roofs shall be designed to avoid flexural fatigue failure caused by design wind loads. Such designs shall be a matter of agreement between the Purchaser and the Manufacturer, using techniques such as underside stitch welding.

**C.3.1.6** All conductive parts of the external floating roof shall be electrically interconnected and bonded to the outer tank structure. Bonding (grounding) shunts shall be provided on the external floating roof and shall be located above the uppermost seal. Shunts shall be 50-mm (2-in.) wide by 28-gauge (0.4-mm [ $1/64$ -in.] thick) austenitic stainless steel as a minimum, or shall provide equivalent corrosion resistance and current carrying capacity as stated in API 2003. Shunt spacing shall be no more than 3 m (10 ft). All movable cover accessories (hatches, manholes, pressure relief devices, and other openings) on the external floating roof shall be electrically bonded to the external floating roof to prevent static electricity sparking when they are opened.

## **C.3.2 Joints**

**C.3.2.1** Joints shall be designed as described in 5.1.

**C.3.2.2** If a lining is applied to the underside of the roof, all joints that will have a lining shall be seal-welded.

## **C.3.3 Decks**

**C.3.3.1** Roofs in corrosive service, such as covering sour crude oil, should be the contact type designed to eliminate the presence of any air-vapor mixture under the deck.

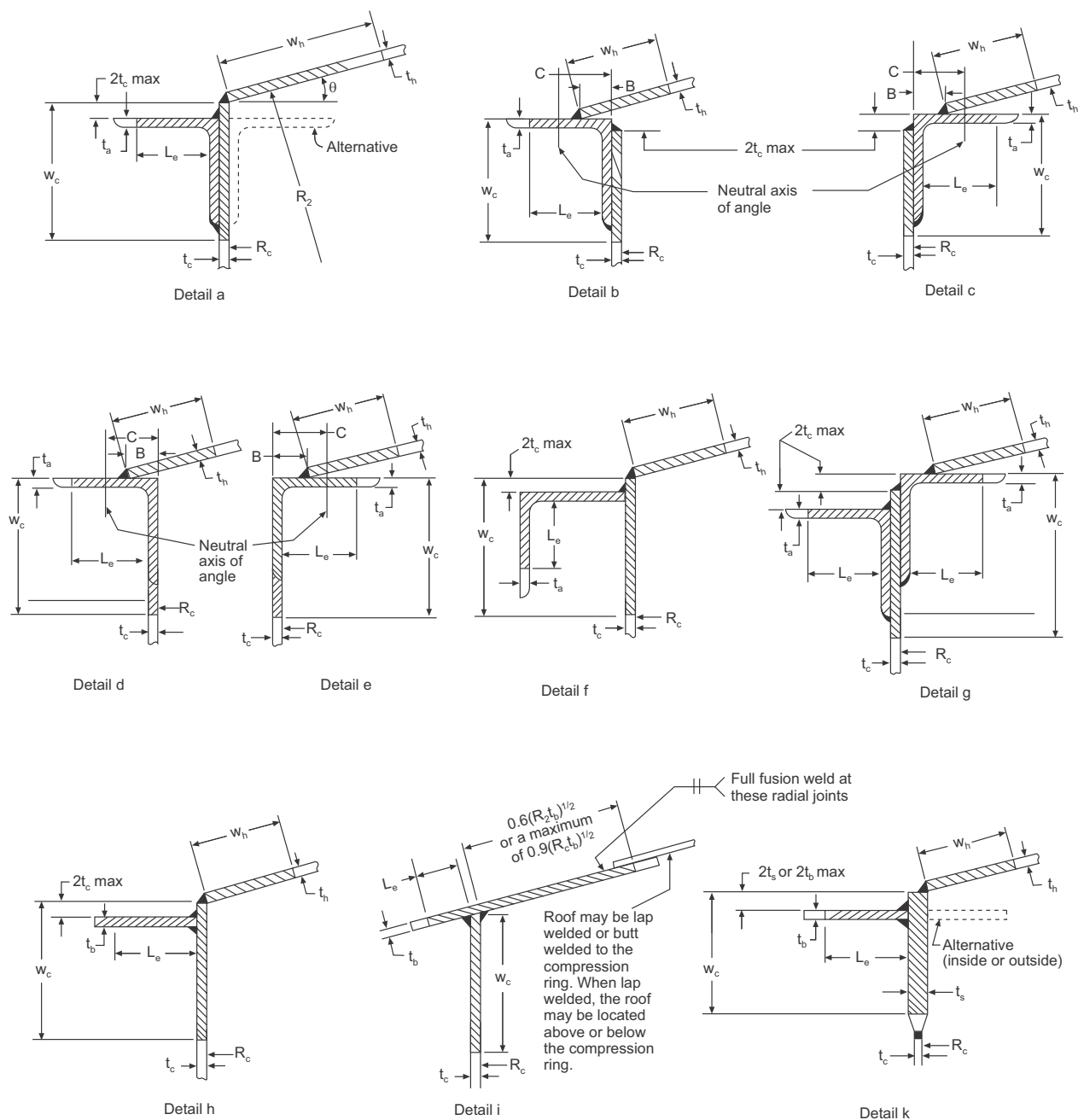
**C.3.3.2** Unless otherwise specified by the Purchaser, all deck plates shall have a minimum nominal thickness of 4.8 mm ( $3/16$  in.) (permissible ordering basis—37.4 kg/m<sup>2</sup>, 7.65 lbf/ft<sup>2</sup> of plate, 0.180-in. plate, or 7-gauge sheet).

**C.3.3.3** Deck plates shall be joined by continuous full-fillet welds on the top side. On the bottom side, where flexure can be anticipated adjacent to girders, support legs, or other relatively rigid members, full-fillet welds not less than 50 mm (2 in.) long on 250 mm (10 in.) centers shall be used on any plate laps that occur within 300 mm (12 in.) of any such members. A minimum of three fillet welds shall be made.

**C.3.3.4** Top decks of double-deck roofs and of pontoon sections, which are designed with a permanent slope shall be designed, fabricated, and erected (with a minimum slope of 1 in 64) to minimize accumulation of standing water (e.g. pooling adjacent to a rolling ladder's track) when primary roof drains are open. This requirement is not intended to completely eliminate isolated puddles. When out of service, water shall flow freely to the primary roof drains. These decks shall preferably be lapped to provide the best drainage. Plate buckles shall be kept to a minimum.

**C.3.3.5** The deck of single-deck pontoon floating roofs shall be designed to be in contact with the liquid during normal operation, regardless of service. The design shall accommodate deflection of the deck caused by trapped vapor.

**C.3.3.6** All covers for roof openings, except roof drains and vents, shall have gaskets or other sealing surfaces and shall be provided with a liquid-tight cover.



$t_a$  = thickness of angle leg  
 $t_b$  = thickness of bar  
 $t_c$  = thickness of shell plate  
 $t_h$  = thickness of roof plate  
 $t_s$  = thickness of thickened plate in shell  
 $t_f$  =  $t_a$  plus  $t_c$  (see note 4)  
 $w_c$  = maximum width of participating shell  
 $= 0.6 (R_c t)^{1/2}$ , where  $t = t_a, t_c, t_s,$  or  $t_f$  as applicable.

$w_h$  = maximum width of participating roof  
 $= 0.3(R_2 t_h)^{1/2}$  or 300 mm (12 in.) whichever is less.  
 $R_c$  = inside radius of tank shell  
 $R_2$  = length of the normal to the roof, measured from the vertical centerline of the tank  $= R_c / (\sin \theta)$   
 $\theta$  = angle between roof and horizontal

**Figure F.2—Permissible Details of Compression Rings**

where

- $P$  is the internal design pressure, in kPa;
- $A$  is the area resisting the compressive force, as illustrated in Figure F.1, in mm<sup>2</sup>;
- $F_y$  is the lowest minimum specified yield strength (modified for design temperature) of the materials in the roof-to-shell junction, in MPa;
- $\theta$  is the angle between the roof and a horizontal plane at the roof-to-shell junction, in degrees;
- $\tan \theta$  is the slope of the roof, expressed as a decimal quantity;
- $D_{LR}$  is the nominal weight of roof plate plus any attached structural, in N.

In USC units:

$$P = \frac{(0.962)(AF_y)(\tan \theta)}{D^2} + \frac{0.245 D_{LR}}{D^2}$$

where

- $P$  is the internal design pressure, in inches of water;
- $A$  is the area resisting the compressive force, as illustrated in Figure F.2, in inches<sup>2</sup>;
- $F_y$  is the lowest minimum specified yield strength (modified for design temperature) of the materials in the roof-to-shell junction, in lb/inch<sup>2</sup>;
- $\theta$  is the angle between the roof and a horizontal plane at the roof-to-shell junction, in degrees;
- $\tan \theta$  is the slope of the roof, expressed as a decimal quantity;
- $D_{LR}$  is the nominal weight of roof plate plus any attached structural, lbf.

**F.4.2** For unanchored tanks, the maximum design pressure, limited by uplift at the base of the shell, shall not exceed the value calculated from the following equation unless further limited by F.4.3:

In SI units:

$$P_{\max} = \frac{0.000849 D_{LS}}{D^2} + \frac{0.00127 D_{LR}}{D^2} - \frac{0.00153 M_w}{D^3}$$

where

- $P_{\max}$  is the maximum design internal pressure, in kPa;
- $D_{LS}$  is the nominal weight of the shell and any framing (but not roof plates) supported by the shell and roof, in N;
- $M_w$  is the wind moment, in N-m;
- $D_{LR}$  is the nominal weight of roof plate plus any attached structural, in N.



## **Annex M** (normative)

### **Requirements for Tanks Operating at Elevated Temperatures**

#### **M.1 Scope**

**M.1.1** This Annex specifies additional requirements for API Standard 650 tanks with a maximum design temperature exceeding 93 °C (200 °F) but not exceeding 260 °C (500 °F).

**M.1.2** The following shall not be used for a maximum design temperature above 93 °C (200 °F):

- a) Open-top tanks (see 5.9).
- b) Floating-roof tanks (see Annex C).
- c) Structurally-supported aluminum dome roofs (see G.1.1 and note below).
- d) Internal floating roofs constructed of aluminum (see H.2.2 and note below).
- e) Internal floating roofs constructed of composite material (see H.2.2). Lower temperature limits may apply for this roof material type.

- **NOTE** An exception may be made by the Purchaser for Items c and d, if the following criteria are met:

- a) Allowable stress reductions for aluminum alloys are determined in accordance with Annex AL, and alloys are evaluated for the potential of exfoliation.
- b) Gaskets and seals are evaluated for suitability at the maximum design temperature.

**M.1.3** Internal floating roofs in accordance with Annex H may be used for a maximum design temperature above 93 °C (200 °F), subject to the applicable requirements of this Annex. The vapor pressure of the liquid must be considered. Sealing devices, particularly those of fabric and nonmetallic materials, shall be suitable for the maximum design temperature.

**M.1.4** Tanks for small internal pressures in accordance with Annex F may be used for a maximum design temperature above 93 °C (200 °F), subject to the requirements of M.3.6, M.3.7, and M.3.8.

**M.1.5** Shop-assembled tanks in accordance with Annex J may be used for a maximum design temperature above 93 °C (200 °F), subject to the applicable requirements of this Annex.

**M.1.6** The nameplate of the tank shall indicate that the tank is in accordance with this Annex by the addition of M to the information required by 10.1.1. In addition, the nameplate shall be marked with the maximum design temperature in the space indicated in Figure 10.1.

- **M.2 Thermal Effects**

This Annex does not provide detailed rules for limiting loadings and strains resulting from thermal effects, such as differential thermal expansion and thermal cycling, that may exist in some tanks operating at elevated temperatures. Where significant thermal effects will be present, it is the intent of this Annex that the Purchaser define such effects. The Manufacturer shall propose, subject to the Purchaser's acceptance, details that will provide strength and utility equivalent to those provided by the details specified by this standard in the absence of such effects.

For a maximum design temperature above 93 °C (200 °F), particular consideration should be given to the following thermal effects.

- a) Temperature differences between the tank bottom and the lower portion of the shell. Such thermal differences may result from factors such as the method and sequence of filling and heating or cooling, the degree of internal circulation, and heat losses to the foundation and from the shell to the atmosphere. With such temperature differences, it may be necessary to provide for increased piping flexibility, an improved bottom-to-shell joint, and a thicker annular ring or bottom sketch plates to compensate for increased rotation of the bottom-to-shell joint (see M.4.2).
- b) The ability of the bottom to expand thermally, which may be limited by the method of filling and heating. With such a condition, it may be necessary to provide improved bottom welding in addition to the details suggested in Item a.
- c) Temperature differences or gradients between members, such as the shell and the roof or stairways, the shell and stiffeners, the roof or shell and the roof supports, and locations with insulation discontinuities.
- d) Whether or not the contents are allowed to solidify and are later reheated to a liquid, including the effect on columns, beams, and rafters. The possible build-up of solids on these components and the potential for plugging of the vent system should also be considered.
- e) The number and magnitude of temperature cycles the tank is expected to undergo during its design life.

### M.3 Modifications in Stress and Thickness

**M.3.1** For a maximum design temperature not exceeding 93 °C (200 °F), the allowable stress specified in 5.6.2 (see Table 5.2a and Table 5.2b) for calculating shell thickness need not be modified.

**M.3.2** For a maximum design temperature exceeding 93 °C (200 °F), the allowable stress specified in 5.6.2 shall be modified as follows: The allowable stress shall be two-thirds the minimum specified yield strength of the material multiplied by the applicable reduction factor given in Table M-1a and Table M-1b or the value given in Table 5.2a and Table 5.2b for product design stress, whichever is less.

**M.3.3** For operating temperatures exceeding 93 °C (200 °F), the yield strength  $F_y$  in 5.10.4.4 shall be multiplied by the applicable reduction factor given in Table M.1a and Table M.1b.

**M.3.4** The allowable stress of 145 MPa (21,000 lbf/in<sup>2</sup>) in the equation for shell-plate thickness in A.4.1 shall be multiplied by the applicable reduction factor given in Table M.1a and Table M.1b.

**M.3.5** The requirements of 5.7.5 for shell manholes, 5.7.7 for flush-type cleanout fittings and of 5.7.8 for flush-type shell connections shall be modified. The thickness of bottom reinforcing plate for flush-type shell cleanouts and flush-type shell connections and bolting flange and cover plates for shell manhole and flush-type shell cleanouts shall be multiplied by the ratio of 205 MPa (30,000 lbf/in.<sup>2</sup>) to the material yield strength at the maximum design temperature if the ratio is greater than one.

**M.3.6** The structural allowable stresses specified in 5.10.3, including the allowable stresses dependent on the modulus of elasticity, shall be multiplied by the yield strength reduction factors from Table M-1a and Table M-1b at the maximum design temperature.

**M.3.7** If the anchors are insulated, the allowable stresses specified in Table 5.21a and Table 5.21b shall be multiplied by the ratio of the material's yield strength at the maximum design temperature to 205 MPa (30,000 lbf/in.<sup>2</sup>) if the ratio is less than 1.0 (see Tables M.1a and M.1b for yield strength reduction factors).

$$\theta_L = \frac{M_L}{K_L} - \tan^{-1} \left( \frac{F_R}{LK_R} \right) + \theta$$

$$\theta_C = \frac{M_C}{K_C}$$

$K_R$ ,  $K_L$ , and  $K_C$  are the shell stiffness coefficients determined from Figures P.2a through P.2l.  $W_R$ ,  $\theta_L$ , and  $\theta_C$  are the resultant radial deflection and rotation of the shell at the opening connection resulting from the piping loads  $F_R$ ,  $M_L$ , and  $M_C$  and the product head, pressure, and uniform or differential temperature between the shell and the tank bottom.  $F_R$ ,  $M_L$ , and  $M_C$  shall be obtained from analyses of piping flexibility based on consideration of the shell stiffness determined from Figures P.2a through P.2l, the shell deflection and rotation determined as described in P.2.5.1 and P.2.5.2, and the rigidity and restraint of the connected piping system.

## P.2.7 Determination of Allowable Loads for the Shell Opening

### P.2.7.1 Construction of Nomograms

**P.2.7.1.1** Determine the nondimensional quantities  $X_A/(Rt)^{0.5}$ ,  $X_B/(Rt)^{0.5}$ , and  $X_C/(Rt)^{0.5}$  for the opening configuration under consideration.

**P.2.7.1.2** Lay out two sets of orthogonal axes on graph paper, and label the abscissas and ordinates as shown in Figure P.3a and Figure P.3b, where  $Y_C$ ,  $Y_F$ , and  $Y_L$  are coefficients determined from Figure P.4a and Figure P.4b.

**P.2.7.1.3** Construct four boundaries for Figure P.3a and two boundaries for Figure P.3b. Boundaries  $b_1$  and  $b_2$  shall be constructed as lines at 45-degree angles between the abscissa and the ordinate. Boundaries  $c_1$ ,  $c_2$ , and  $c_3$  shall be constructed as lines at 45-degree angles passing through the calculated value indicated in Figure P.3a and Figure P.3b plotted on the positive x axis.

### P.2.7.2 Determination of Allowable Loads

**P.2.7.2.1** Use the values for  $F_R$ ,  $M_L$ , and  $M_C$  obtained from the piping analyses to determine the quantities  $(\lambda 2Y_F)(F_R/F_P)$ ,  $(\lambda aY_L)(M_L/F_P)$ , and  $(\lambda aY_C)(M_C/F_P)$ .

**P.2.7.2.2** Plot the point  $(\lambda 2Y_F)(F_R/F_P)$ ,  $(\lambda aY_L)(M_L/F_P)$  on the nomogram constructed as shown in Figure P.5a.

**P.2.7.2.3** Plot the point  $(\lambda 2Y_F)(F_R/F_P)$ ,  $(\lambda aY_L)(M_C/F_P)$  on the nomogram constructed as shown in Figure P.5b.

**P.2.7.2.4** The external piping loads  $F_R$ ,  $M_L$ , and  $M_C$  to be imposed on the shell opening are acceptable if both points determined from P.2.7.2.2 and P.2.7.2.3 lie within the boundaries of the nomograms constructed for the particular opening-tank configuration.

## P.2.8 Manufacturer and Purchaser Responsibility

- **P.2.8.1** The Manufacturer is responsible for furnishing to the Purchaser the shell stiffness coefficients (see P.2.4) and the unrestrained shell deflection and rotation (see P.2.5). The Purchaser is responsible for furnishing to the Manufacturer the magnitude of the shell-opening loads (see P.2.6). The Manufacturer shall determine, in accordance with P.2.7, the acceptability of the shell-opening loads furnished by the Purchaser. If the loads are excessive, the piping configuration shall be modified so that the shell-opening loads fall within the boundaries of the nomograms constructed as in P.2.7.1.

### S.3.6 Annex M—Modifications

**S.3.6.1** Annex M requirements shall be met for stainless steel tanks with a maximum design temperature over 40 °C (100 °F) as modified by S.3.6.2 through S.3.6.7.

**S.3.6.2** Allowable shell stress shall be in accordance with Table S.2a and Table S.2b.

**S.3.6.3** In M.3.5, the requirements of 5.7.7 for flush-type cleanout fittings and of 5.7.8 for flush-type shell connections shall be modified. The thickness of the bottom reinforcing plate, bolting flange, and cover plate shall be multiplied by the greater of (a) the ratio of the material yield strength at 40 °C (100 °F) to the material yield strength at the maximum design temperature, or (b) the ratio of 205 MPa (30,000 psi) to the material yield strength at the maximum design temperature. (See Table S.5a and Table S.5b for yield strength.)

**S.3.6.4** In M.3.6, the stainless steel structural allowable stress shall be multiplied by the ratio of the material yield strength at the maximum design temperature to the material yield strength at 40 °C (100 °F). (See Tables S.5a and S.5b for yield strength.)

**S.3.6.5** In M.5.1, the requirements of 5.10.5 and 5.10.6 shall be multiplied by the ratio of the material modulus of elasticity at 40 °C (100 °F) to the material modulus of elasticity at the maximum design temperature. (See Tables S.6a and S.6b for modulus of elasticity.)

**S.3.6.6** In M.6 (the equation for the maximum height of unstiffened shell in 5.9.7.1), the maximum height shall be multiplied by the ratio of the material modulus of elasticity at the maximum design temperature to the material modulus of elasticity at 40 °C (100 °F).

## S.4 Fabrication and Construction

### S.4.1 General

Special precautions must be observed to minimize the risk of damage to the corrosion resistance of stainless steel. Stainless steel shall be handled so as to minimize contact with iron or other types of steel during all phases of fabrication, shipping, and construction. The following sections describe the major precautions that should be observed during fabrication and handling.

### S.4.2 Storage

Storage should be under cover and well removed from shop dirt and fumes from pickling operations. If outside storage is necessary, provisions should be made for rainwater to drain and allow the material to dry. Stainless steel should not be stored in contact with carbon steel. Materials containing chlorides, including foods, beverages, oils, and greases, should not come in contact with stainless steel.

### S.4.3 Thermal Cutting

**S.4.3.1** Thermal cutting of stainless steel shall be by the iron powder burning carbon arc or the plasma-arc method.

- **S.4.3.2** Thermal cutting of stainless steel may leave a heat-affected zone and intergranular carbide precipitates. This heat-affected zone may have reduced corrosion resistance unless removed by machining, grinding, or solution annealing and quenching. The Purchaser shall specify if the heat-affected zone is to be removed.

### S.4.4 Forming

**S.4.4.1** Stainless steels shall be formed by a cold, warm, or hot forming procedure that is noninjurious to the material.

Table S.2a—Allowable Stresses for Tank Shells (SI)

Type	Min. Yield MPa	Min. Tensile MPa	Allowable Stress ( $S_d$ ) (in MPa) for Maximum Design Temperature Not Exceeding					
			40 °C	90 °C	150 °C	200 °C	260 °C	$S_t$ Ambient
201-1	260	515	155	136	125	121	—	234
201LN	310	655	197	172	153	145	143	279
304	205	515	155	155	140	128	121	186
304L	170	485	145	132	119	109	101	155
316	205	515	155	155	145	133	123	186
316L	170	485	145	131	117	107	99	155
317	205	515	155	155	145	133	123	186
317L	205	515	155	155	145	133	123	186

NOTE 1  $S_d$  may be interpolated between temperatures.

- NOTE 2 The design stress shall be the lesser of 0.3 of the minimum tensile strength or 0.9 of the minimum yield strength. The factor of 0.9 of yield corresponds to a permanent strain of 0.10 %. When a lower level of permanent strain is desired, the Purchaser shall specify a reduced yield factor in accordance with Table Y-2 of ASME Section II, Part D. The yield values at the different maximum design temperatures can be obtained from Table S.5a.
- NOTE 3 For dual-certified materials (e.g. ASTM A182M/A182 Type 304L/304), use the allowable stress of the grade specified by the Purchaser.

Table S.2b—Allowable Stresses for Tank Shells (USC)

Type	Min. Yield psi	Min. Tensile psi	Allowable Stress ( $S_d$ ) (in psi) for Maximum Design Temperature Not Exceeding					
			100 °F	200 °F	300 °F	400 °F	500 °F	$S_t$ Ambient
201-1	38,000	75,000	22,500	19,700	18,100	17,500	--	34,200
201LN	45,000	95,000	28,500	24,900	22,200	21,100	20,700	40,500
304	30,000	75,000	22,500	22,500	20,300	18,600	17,500	27,000
304L	25,000	70,000	21,000	19,200	17,200	15,800	14,700	22,500
316	30,000	75,000	22,500	22,500	21,000	19,300	17,900	27,000
316L	25,000	70,000	21,000	19,000	17,000	15,500	14,300	22,500
317	30,000	75,000	22,500	22,500	21,000	19,300	17,900	27,000
317L	30,000	75,000	22,500	22,500	21,000	19,300	17,900	27,000

NOTE 1  $S_d$  may be interpolated between temperatures.

- NOTE 2 The design stress shall be the lesser of 0.3 of the minimum tensile strength or 0.9 of the minimum yield strength. The factor of 0.9 of yield corresponds to a permanent strain of 0.10 %. When a lower level of permanent strain is desired, the Purchaser shall specify a reduced yield factor in accordance with Table Y-2 of ASME Section II, Part D. The yield values at the different maximum design temperatures can be obtained from Table S.5b.
- NOTE 3 For dual-certified materials (e.g. ASTM A182M/A182 Type 304L/304), use the allowable stress of the grade specified by the Purchaser.

$G_{out}$  is the unit weight of flood liquid, in  $\text{kg/m}^3$  ( $\text{lb/ft}^3$ ) ( $1000 \text{ kg/m}^3$  [ $62.4 \text{ lb/ft}^3$ ] for water);

$H$  is the shell height, in m (ft);

$h_1, h_2, \dots, h_n$  is the height of shell courses 1, 2, 3, through n, respectively, in m (ft);

$H_{in}$  is the height or depth of liquid inside tank, in m (ft);

$H_{safe}$  is the maximum height of unstiffened shell permitted, based on  $t_{smin}$ , in m (ft);

$H_{TS}$  is the Transformed height of tank shell, in m (ft);

$I_{act}$  is the The actual moment of inertia of the stiffener ring region, in  $\text{cm}^4$  ( $\text{in.}^4$ );

$I_{reqd}$  is the required moment of inertia of the stiffener ring, in  $\text{cm}^4$  ( $\text{in.}^4$ );

$L_1, L_2$  is the distances between adjacent intermediate stiffeners or intermediate stiffener and top of shell or bottom of shell, respectively, in m (ft);

$L_r$  is the minimum roof live load on horizontal projected area of the roof,  $\text{kPa}$  ( $\text{lb/ft}^2$ ) =  $1.0 \text{ kPa}$  ( $20 \text{ lb/ft}^2$ );

$L_s$  equals  $(L_1 + L_2)/2$ , in m (ft);

$N$  is the number of waves into which a shell will buckle under external pressure;

$N_s$  is the number of intermediate stiffeners;

$P_e$  is the specified external pressure, in  $\text{kPa}$  ( $\text{lb/ft}^2$ );

$P_r$  is the total design external pressure for design of roof, in  $\text{kPa}$  ( $\text{lb/ft}^2$ );

$P_s$  is the total design external pressure for design of shell, in  $\text{kPa}$  ( $\text{lb/ft}^2$ ).  $P_s$  = the greater of 1) the specified design external pressure,  $P_e$ , excluding wind or 2)  $W + 0.4P_e$  (see 5.2.2 for an important consideration);

$\psi$  is the stability factor (see V.8.1 for values);

$Q$  is the radial load imposed on the intermediate stiffener by the shell, in  $\text{N/m}$  ( $\text{lb/in.}$ );

$q_s$  is the first moment of area of stiffener for design of stiffener attachment weld, in  $\text{cm}^3$  ( $\text{in.}^3$ );

$R$  is the roof dish radius, in m (ft);

$S$  is the specified snow load, in  $\text{kPa}$  ( $\text{lb/ft}^2$ );

$S_d$  is the allowable design stress, in  $\text{MPa}$ , ( $\text{lb/in.}^2$ );

$t$  is the nominal shell thickness, mm ( $\text{in.}$ );

$t_b$  is the nominal thickness of bottom plate under the shell, in mm ( $\text{in.}$ );

$t_{cone}$  is the required nominal thickness of cone roof plate, in mm ( $\text{in.}$ ). Maximum corroded thickness shall be 12.5 mm (0.5 in.);

**V.7.3.3** The length of dome or umbrella roof considered to be within the top tension/compression ring region is determined by the following equation:

In SI units:

$$X_{\text{dome}} = 19.0 \sqrt{RT_{\text{dome}}}$$

In USC units:

$$X_{\text{dome}} = 2.1 \sqrt{RT_{\text{dome}}}$$

**V.7.3.4** The length of shell considered to be within the top tension/compression ring region is determined by the following equation (see Figure V.1b):

In SI units:

$$X_{\text{shell}} = 13.4 \sqrt{Dt_{s1}}$$

In USC units:

$$X_{\text{shell}} = 1.47 \sqrt{Dt_{s1}}$$

**V.7.3.5** The required cross-sectional area of the top stiffener structural shape is determined by the following equation:

$$A_{\text{stiff}} = A_{\text{reqd}} - t_{s1}X_{\text{shell}} - t_{\text{dome}}X_{\text{dome}}$$

NOTE This value should be recalculated, if necessary, after selection of final shell thickness.

## V.8 Shell

### • V.8.1 Unstiffened Shells

The procedure utilizes the nominal thickness of thinnest shell course and the transformed shell method to establish intermediate stiffener number and locations. The equations in V.8.1.2 and V.8.1.3 contain variables for a stability factor,  $\psi$ , that is dependent upon the magnitude of the vacuum pressure. The equations also include a 0.8 “knockdown” factor for imperfections in the cylindrical shell geometry. Shells shall be checked for two conditions: 1) the combined wind plus vacuum, and 2) for vacuum pressure alone. Each condition shall be checked using the appropriate stability factor,  $\psi$ , as follows.

**V.8.1.2** The design external pressure (using the appropriate  $\psi$  from V.8.1) and the specified external (vacuum) pressure (using  $\psi = 3.0$ ) shall not exceed for an unstiffened tank:

In SI units:

$$P_s \text{ or } P_e \leq \frac{E}{15,203 \psi \left(\frac{H_{TS}}{D}\right) \left(\frac{D}{t_{s\min}}\right)^{2.5}}$$

In USC units:

$$P_s \text{ or } P_e \leq \frac{0.6E}{\psi \left(\frac{H_{TS}}{D}\right) \left(\frac{D}{t_{s\min}}\right)^{2.5}}$$

**V.8.1.3** The equation in V.8.1.2 can be rewritten to calculate the nominal thickness of the thinnest shell course required for a specified design external pressure as:

In SI units:

$$t_{s\min} \geq \frac{47.07 (\psi H_{TS} P_s)^{0.4} D^{0.6}}{(E)^{0.4}}$$

In USC units:

$$t_{s\min} \geq \frac{1.23 (\psi H_{TS} P_s)^{0.4} D^{0.6}}{(E)^{0.4}}$$

**V.8.1.4** For tanks with shell courses of varying thickness, the transformed shell height,  $H_{TS}$ , for the tank shell is determined in accordance with the following procedure:

- a) The transformed height of the shell is calculated as the sum of the transformed widths of the individual shell courses as described in Item b.
- b) The transformed width of each individual shell course is calculated by multiplying the actual shell height by the ratio  $(t_{s1}/t_{act})^{2.5}$ . Note that  $t_{s1} = t_{act}$  for the top shell course.

The transformed shell height is determined from the following equation:

$$H_{TS} = h_1 \left(\frac{t_{s1}}{t_{s1}}\right)^{2.5} + h_2 \left(\frac{t_{s1}}{t_{s2}}\right)^{2.5} + \dots + h_n \left(\frac{t_{s1}}{t_{sn}}\right)^{2.5}$$

The transformed shell height is an analytical model of the actual tank. The transformed shell has a uniform thickness equal to the topmost shell thickness and a height equal to the transformed height. This analytical model of the actual tank will have essentially an equivalent resistance to buckling from external pressure as the actual tank.



Intermediate stiffener spacings on 0.328 in. and 0.395 in. shell plate are,

$$L_s = [H_{\text{Safe}}](t_{\text{sx}}/t_{\text{smin}})^{2.5}$$

$$L_s = [5.84](0.328/0.3125)^{2.5} = 6.59 \text{ ft}$$

$$L_s = [5.84](0.395/0.3125)^{2.5} = 10.49 \text{ ft}$$

For equal transposed width we would like to locate 5 stiffeners on 0.3125 in. shell at spacing = 5.44 ft. However, this causes the 3<sup>rd</sup> stiffener (location = 5.44 ft  $\times$  3 = 16.32 ft) to be closer to the horizontal shell seam than we would prefer. Therefore, we will try to locate the 5 stiffeners on the 0.3125 in. shell at spacing = 5.75 ft (must be less than or equal to  $L_s = 5.84$  ft).

Locate the 6<sup>th</sup> stiffener as follows:

$$\text{Available 0.3125-in. shell plate} = (4 \times 8 \text{ ft}) - (5 \times 5.75 \text{ ft}) = 3.25 \text{ ft}$$

$$\text{Maximum length of 0.328-in. shell} = (5.84 - 3.25) \times (0.328 / 0.3125)^{2.5} = 2.92 \text{ ft}$$

6<sup>th</sup> stiffener must be located no more than 2.92 ft on 0.328-in. shell. Stiffener can be located 1.5 ft on 0.328-in. shell

$$\text{Location of 6}^{\text{th}} \text{ stiffener} = 32 + 1.5 = 33.5 \text{ ft from top of tank}$$

Locate the 7<sup>th</sup> stiffener as follows:

$$\text{Available 0.328-in. shell} = (5 \times 8) - 33.5 = 6.5 \text{ ft}$$

$$\text{Maximum spacing on 0.328-in. shell} = L_s = 6.59 \text{ ft}$$

To keep stiffener away from horizontal shell seam, locate stiffener less than 6.59 ft.

$$\text{Location of 7}^{\text{th}} \text{ stiffener} = 33.5 + 5.75 = 39.25 \text{ ft}$$

Check the remaining unstiffened shell:

$$\text{Difference between actual and transformed shell height} = 48 - 43.54 = 4.45 \text{ ft}$$

$$\text{Length of 0.328-in. shell below stiffener} = 40 - 39.25 = 0.75 \text{ ft}$$

Transformed shell stiffener spacing =  $0.75 \times (0.3125/0.328)^{2.5} + 8.0 \times (0.3125/0.395)^{2.5} = 5.12$  ft. Must be less than or equal to 5.84 ft ( $H_{\text{Safe}}$ ) - OK

**9) If fewer stiffeners and thicker shell plates is a more economical solution, the design can be adjusted as follows:**

Assume, for this example, a uniform shell thickness equal to the thickness of the lowest shell course, i.e.  $t_{\text{avg}} = 0.395$  in.

$H_{\text{safe}}$  is then calculated as follows:

$$H_{\text{safe}} = \frac{0.6(0.395)^{2.5}(30,000,000)}{3(75)^{1.5}(733.36)(86.4)}$$

$$H_{\text{safe}} = 10.48 \text{ ft}$$

For  $t_{\text{avg}} = 0.395$  in.,  $H_{TS}$  is recalculated to be equal to 48 ft.

Table X.2a—Allowable Stresses for Tank Shells (SI)

Alloy	Min Yield	Min Ten	Allowable Stress MPa for Design Temp Not Exceeding ( $S_t$ s)					
	MPa	MPa	40 °C	90 °C	150 °C	200 °C	260 °C	$S_t$ ambient
S31803	450	620	248	248	239	230	225	266
S32003	450	655	262	231	218	215	212	281
S32101	450	650	260	234	223	215	212	278
S32202	450	650	262	258	226	214	209	281
S32205	450	655	262	234	225	208	191	281
S32304	400	600	240	229	213	205	200	257
S32550	550	760	303	302	285	279	272	325
S32520	550	770	308	270	265	256	251	331
S32750	550	795	318	319	298	279	268	343
S32760	550	750	298	314	259	256	256	319

NOTE 1  $S_t$ s may be interpolated between temperatures.

NOTE 2 The design stress shall be the lesser of 2/5 of the minimum tensile strength or 2/3 of the minimum yield strength.

NOTE 3 The hydrotest stress shall be the lesser of 3/7 of the minimum tensile strength or 3/4 of the minimum yield strength.

NOTE 4 For dual certified materials, S31803/S32205 and S32550/S32520, use the allowable stress of the grade specified by the purchaser.

Table X.2b—Allowable Stresses for Tank Shells (USC)

Alloy	Min Yld	Min Ten	Allowable Stress PSI for Design Temp Not Exceeding ( $S_t$ s)					
	lbf/in <sup>2</sup>	lbf/in <sup>2</sup>	100 °F	200 °F	300 °F	400 °F	500 °F	$S_t$ ambient
S31803	65,000	90,000	36,000	36,000	34,700	33,400	32,600	38,600
S32003	65,000	95,000	38,000	33,600	33,600	31,200	30,700	40,800
S32101	65,000	94,000	37,600	34,000	32,400	31,200	30,700	40,300
S32202	65,000	94,000	38,000	37,000	32,900	31,000	30,300	40,800
S32205	65,000	95,000	38,000	34,000	32,700	30,000	28,700	40,800
S32304	58,000	87,000	34,800	33,200	30,900	29,700	29,000	37,300
S32550	80,000	110,000	44,000	43,800	41,400	40,400	39,400	47,200
S32520	80,000	112,000	44,800	39,200	38,400	37,200	36,400	48,000
S32750	80,000	116,000	46,400	46,200	43,200	40,500	38,900	49,800
S32760	80,000	108,000	43,200	39,200	37,600	37,200	37,200	46,300

NOTE 1  $S_t$ s may be interpolated between temperatures.

NOTE 2 The design stress shall be the lesser of 2/5 of the minimum tensile strength or 2/3 of the minimum yield strength.

NOTE 3 The hydrotest stress shall be the lesser of 3/7 of the minimum tensile strength or 3/4 of the minimum yield strength.

NOTE 4 For dual certified materials, S31803/S32205 and S32550/S32520, use the allowable stress of the grade specified by the purchaser.