Annex F
(normative)

Design of Tanks for Small Internal Pressures

F.1 Scope

F.1.1 The maximum internal pressure for closed-top API Standard 650 tanks may be increased to the maximum internal pressure permitted (18 kPa [2.5 lbf/in.^{2}]) gauge when the additional requirements of this Annex are met. This Annex applies to the storage of nonrefrigerated liquids (see also API 620, Annex Q and Annex R). For maximum design temperatures above 93 °C (200 °F), see Annex M.

F.1.2 When the internal pressure multiplied by the cross-sectional area of the nominal tank diameter does not exceed the combined nominal weight of the shell, roof plate, any structural members attached to the roof plate, and any framing supported by the shell, the design requirements in F.2 through F.7 shall be met. Overturning stability with respect to seismic conditions shall be determined independently of internal pressure uplift. Seismic design shall meet the requirements of Annex E.

F.1.3 Internal pressures that exceed the combined nominal weight of the shell, roof plate, any structural members attached to the roof plate, and any framing supported by the shell shall also meet requirements of F.8.

F.1.4 Tanks designed according to this Annex shall comply with all the applicable rules of this standard unless the rules are superseded by the requirements of F.8.

F.1.5 The tank nameplate (see Figure 10.1) shall indicate whether the tank has been designed in accordance with F.1.2 or F.1.3.

F.1.6 Figure F.1 is provided to aid in the determination of the applicability of various sections of this Annex.

F.2 Design Considerations

F.2.1 In calculating shell thickness for Annex F tanks, when selecting shell manhole thicknesses in Table 5.3a and Table 5 3b and flush-type cleanout fitting thicknesses in Table 5.10a and Table 5.10b, and when performing Annex P nozzle calculations, H shall be increased by the quantity $P/(9.8G)$ for SI units, or $P/(12G)$ for USC units—where H is the design liquid height, in m (ft), P is the design pressure kPa (in. of water), and G is the design specific gravity. Design pressures less than 1 kPa (4 in. of water) do not need to be included.

F.2.2 The required compression area at the roof-to-shell junction shall be calculated as in F.5.1, and the participating compression area at the junction shall be determined by Figure F.2. Full penetration butt welds shall be used to connect sections of the compression ring. For self-supporting roofs, the compression area shall not be less than the cross-sectional area calculated in 5.10.5 or 5.10.6 as applicable. Materials for compression areas may be selected from API 650, Section 4, and need not meet toughness criteria of 4.2.9.

F.2.3 Roof plate, manway and nozzle materials shall conform to the specifications in this standard. Materials selected from API-650, Section 4 need not meet toughness criteria of 4.2.9.

F.2.4 For design pressures greater than 2 kPa (8 in. of water), roof manways and roof nozzles shall meet the requirements of API 650, 5.7.1 through 5.7.6, for shell manways and nozzles. When using values from API 650 Table 5.3, the lowest values for the maximum design liquid level (H) may be used. When using equations from API 650 5.7.5.6, maximum design liquid level (H) shall be a minimum of 5 m (18 ft). Alternatively, roof manways and nozzles may be designed per API 620 using all the rules for API 620 roof manways and nozzles, including the 250 °F maximum design temperature limitation.

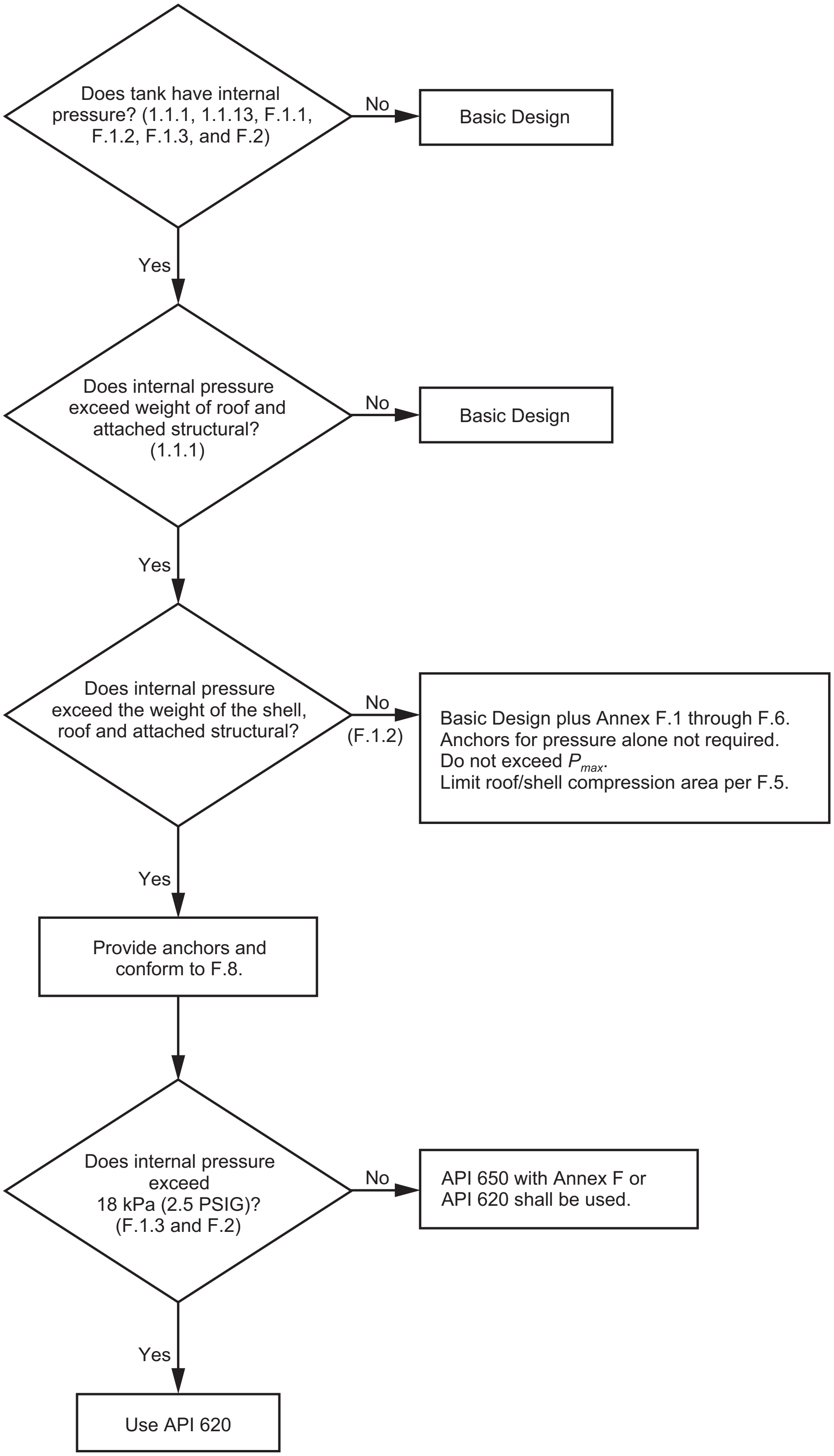
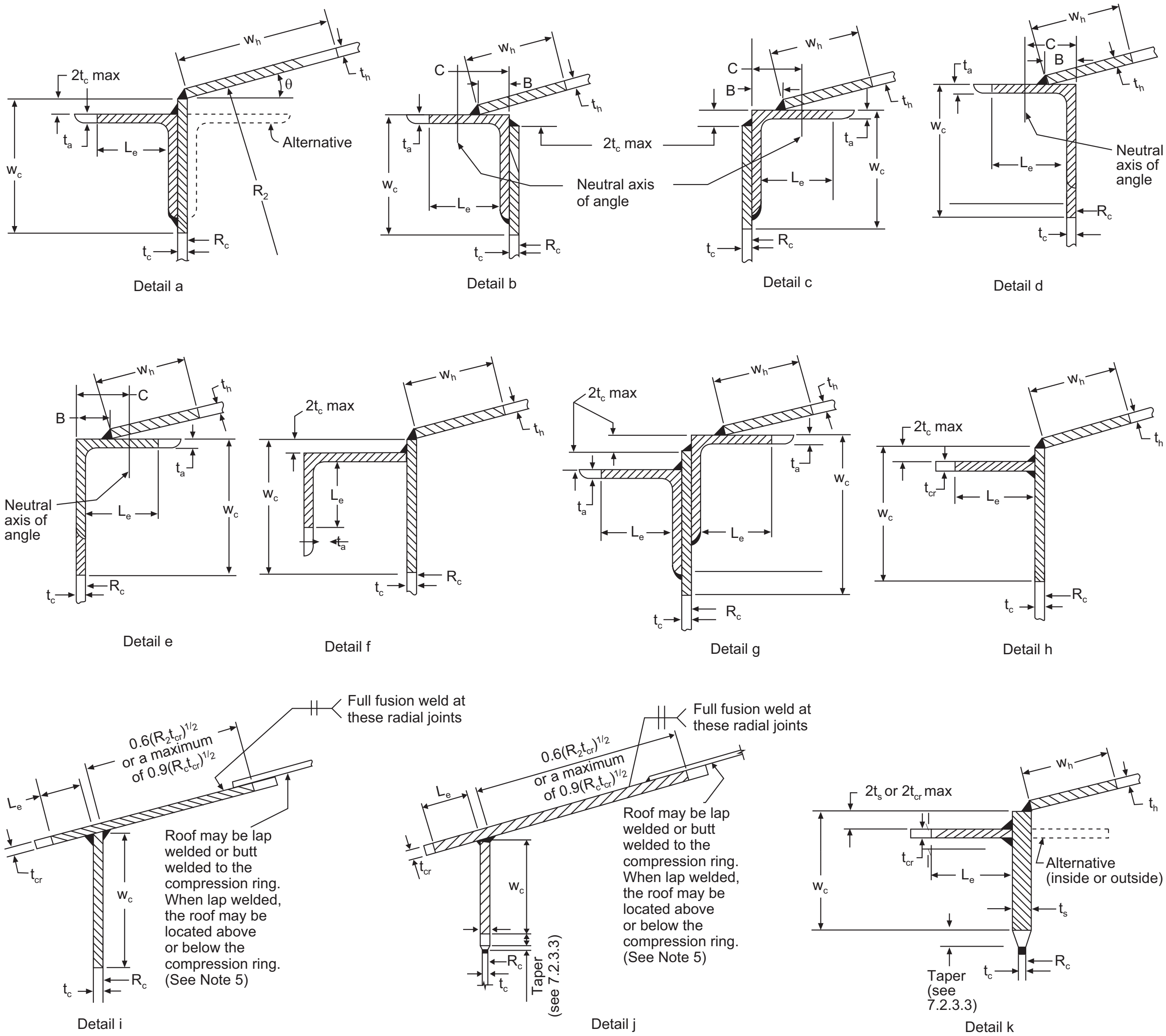


Figure F.1—Annex F Decision Tree



t_a = thickness of angle leg
t_{cr} = 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 θ)
θ = angle between roof and horizontal

NOTE 1 All dimensions and thicknesses are in millimeters (inches).

NOTE 2 Dimension B in details b, c, d, and e is: $0 \leq B \leq C$. C is the dimension to the neutral axis of the angle.

NOTE 3 The unstiffened length of the angle or bar, L_e, shall be limited to $250t/(F_y)^{1/2}$ mm [$3000t/(F_y)^{1/2}$ in.] where F_y is the minimum specified yield strength, MPa (lbf/in.^{2}) and $t = t_a$ or t_b, as applicable.

NOTE 4 Where members are lap welded onto the shell (refer to details a, b, c, and g), t_f may be used in w_c formula only for the extent of the overlap.

NOTE 5 When the lap welded roof plate is located under the compression bar, the Purchaser should consider the use of caulking on top of the fillet weld to ensure the drainage of rainfall.

Figure F.2—Permissible Details of Compression Rings

F.3 Roof Details

The details of the roof-to-shell junction shall be in accordance with Figure F.2, in which the participating area resisting the compressive force is shaded with diagonal lines.

F.4 Maximum Design Pressure and Test Procedure

F.4.1 The maximum design pressure, P, for a tank that has been constructed or that has had its design details established may be calculated from the following equation (subject to the limitations of P_{max} in F.4.2):

In SI units:

$$P = \frac{AF_y \tan\theta}{200D^2} + \frac{0.00127\ D_{LR}}{D^2}$$

where

- P is the internal design pressure, in kPa;
- A is the participating area at the roof-to-shell joint based on the corroded thickness, determined using Figure F.2, in mm^2;
- F_y is the lowest minimum specified yield strength (modified for design temperature) of the materials in the roof-to-shell junction, in MPa;
- θ 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 structural members attached to the roof plate, 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 participating area at the roof-to-shell joint based on the corroded thickness, determined using Figure F.2, in inches^2;
- 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^2;
- θ 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 structural members attached to the roof plate, in lbf.

F.4.2 For self-anchored tanks, the maximum design pressure, limited by uplift at the base of the shell, shall not exceed the value calculated from the following equations as applicable unless further limited by F.4.3:

For self-anchored fixed roof tanks except supported cone roof tanks, the maximum design pressure (P_{max}) shall be the minimum of (3) cases:

(1) $$\frac{\beta}{D^3}\left(\frac{M_{DL}}{1.5} + M_{DLR} - 0.6\ M_w\right)$$

(2) $$\frac{\beta}{F_p \cdot D^3}\left(\frac{M_{DL} + M_F}{2} + M_{DLR} - M_w\right)$$

(3) $$\frac{\beta}{F_p \cdot D^3}\left(\frac{M_{DL}}{1.5} + M_{DLR} - M_{ws}\right)$$

For self-anchored supported cone roof tanks:

$$P_{max} = \frac{\beta}{F_p \cdot D^3}\left(\frac{M_{DL}}{1.5} + M_{DLR} - M_{ws}\right)$$

where

D is the tank diameter, m (ft);

β is the conversion factor: for SI = [8/(π × 1000)], for USC = [(8 × 12)/(π × 62.4)];

F_p is the pressure combination factor, see 5.2.2;

M_{DL} is moment about the shell-to-bottom joint from the nominal weight of the shell and roof structural supported by the shell that is not attached to the roof plate, N × m (ft × lbf);

M_{DLR} is the moment about the shell-to-bottom joint from the nominal weight of the roof plate plus any structural components attached to the roof, N × m (ft × lbf);

M_F is the moment about the shell-to-bottom joint from liquid weight per 5.11.2.3, N × m (ft × lbf);

M_w is the overturning moment about the shell-to-bottom joint from horizontal plus vertical wind pressure, N × m (ft × lbf);

M_{ws} is the overturning moment about the shell-to-bottom joint from horizontal wind pressure, N × m (ft × lbf);

P_{max} is the maximum design pressure kPa (inches of water).

F.4.3 As top angle size and roof slope decrease and tank diameter increases, the design pressure permitted by F.4.1 and F.4.2 approaches the failure pressure of F.7 for the roof-to-shell junction. In order to provide a safe margin between the maximum operating pressure and the calculated failure pressure, a suggested further limitation on the maximum design pressure for tanks with a weak roof-to-shell attachment (frangible joint) is:

$$P_{max} \le 0.8 P_f$$

F.4.4 When the entire tank is completed, it shall be filled with water to the top angle or the design liquid level, and the design internal air pressure shall be applied to the enclosed space above the water level and held for 15 minutes. The air pressure shall then be reduced to one-half the design pressure, and all welded joints above the liquid level shall be checked for leaks by means of a soap film, linseed oil, or another suitable material. Tank vents shall be tested during or after this test.

F.5 Required Compression Area at the Roof-to-Shell Junction

F.5.1 Where the maximum design pressure has already been established (not higher than that permitted by F.4.2 or F.4.3, whenever applicable), the total required compression area at the roof-to-shell junction shall be calculated from the following equation:

In SI units:

$$A = \frac{200D^2\left(P_i - \frac{0.00127\ D_{LR}}{D^2}\right)}{F_y(\tan\theta)}$$

where

A is the total required compression area at the roof-to-shell junction, in mm^2. A is based on the corroded thickness;

P_i is the design internal pressure, in kPa;

D_{LR} is the nominal weight of roof plate plus any attached structural, in N.

In USC units:

$$A = \frac{D^2\left(P_i - \frac{0.245\ D_{LR}}{D^2}\right)}{0.962F_y\ (\tan\theta)}$$

where

A is the total required compression area at the roof-to-shell junction, in inches^2. A is based on the corroded thickness;

P_i is the design internal pressure, in inches of water;

D_{LR} is the nominal weight of roof plate plus any attached structural, in lbf;

A is based on the nominal material thickness less any corrosion allowance.

F.5.2 For self-supporting roofs, the compression area shall not be less than the cross-sectional area calculated in 5.10.5 and 5.10.6.

F.6 Design of Roof Plates

F.6.1 Minimum thickness of supported and self-supporting cone roofs under internal pressure shall be calculated as follows:

$$t = \frac{(P \times R_t)}{\cos\alpha \times S_d \times E} + C_a$$

where

t is the minimum roof thickness required for internal pressure in mm (in.);

P is the internal Design pressure – minus effect of nominal roof dead load in kPa (lbf/in.^{2});

R_t is the nominal tank radius in m (in.);

a is the half apex angle of cone roof (degrees);

$\cos\alpha$ is the cosine of half apex angle expressed as a decimal quantity;

S_d is the allowable stress for the design condition per this Standard in MPa, (lbf/in.^{2});

E is the joint efficiency:

E = 0.35 for full fillet lap welded plate from top side only,

E = 0.65 for full fillet lap welded plate from both sides,

E = 0.70 for full-penetration, complete-fusion butt welded plates with or without backing strip,

E = 0.85 for full-penetration, complete-fusion butt welded plates with spot radiography in accordance with 8.1.2.2,

E = 1.0 for full-penetration, complete-fusion butt welded plates with 100% full radiography;

• C_a is the corrosion allowance in mm (in.) as specified by the Purchaser (see 5.3.2).

NOTE 1 Thickness (t) of lap welded plates when controlled by internal pressure design shall not exceed 13 mm ($^1/_2$ in.) excluding corrosion allowance.

NOTE 2 Calculated thickness (t) of roof plates shall not be less than that required under 5.10.4 for supported cone or less than that required under 5.10.5 for self-supporting cone roofs.

F.6.2 Minimum thickness of self-supporting dome and umbrella roofs under internal pressure shall be calculated as follows:

$$t = \frac{\gamma \times (P \times R_R)}{S_d \times E} + C_a$$

where

t is the minimum roof thickness required for internal pressure in mm (in.);

γ is the Shape factor:

γ = 0.50 for dome roofs with spherical shape (double radius of curvature),

γ = 1.0 for umbrella roofs (single radius of curvature);

P is the internal Design pressure – minus effect of nominal roof dead load in kPa (lbf/in^2);

R_R is the roof radius in m (in.);

S_d is the allowable stress for the design condition per this Standard in MPa (lbf/in²);

E is the joint efficiency:

E = 0.35 for full fillet lap welded plate from top side only,

E = 0.65 for full fillet lap welded plate from both sides,

E = 0.70 for full penetration, complete fusion butt welded plates with or without backing strip,

E = 0.85 for full-penetration, complete-fusion butt welded plates with spot radiography in accordance with 8.1.2.2,

E = 1.0 for full-penetration, complete-fusion butt welded plates with 100 % full radiography;

• C_a is the corrosion allowance in mm (in.) as specified by the Purchaser (see 5.3.2).

NOTE 1 Thickness (t) of lap welded plates when controlled by internal pressure design shall not exceed 13 mm (1/2 in.) excluding corrosion allowance.

NOTE 2 Calculated thickness (t) of roof plates shall not be less than that required under 5.10.6 for self-supporting dome and umbrella roofs.

NOTE 3 An alternate analysis technique (such as finite element analysis) of the roof is acceptable, as long as the allowable stresses and joint efficiencies referenced above are applied to define the minimum thickness. Notes 1 and 2 shall still apply.

• **F.6.3** The rules in F.6.1 and F.6.2 cannot cover all details of tank roof design and construction. With the approval of the Purchaser, the roof need not comply with F.6. The manufacturer shall provide a roof designed and constructed to be as safe as otherwise provided for in this standard.

F.7 Calculated Failure Pressure

For tanks that meet the criteria of 5.10.2.6, failure of the roof-to-shell junction can be expected to occur when the stress in the compression ring area reaches the yield point. On this basis, an approximate formula for the pressure at which failure of the top compression ring is expected (using conservative effective areas) to occur can be expressed in terms of the design pressure permitted by F.4.1, as follows:

In SI units:

$$P_f = 1.6P - \frac{0.000746\ D_{LR}}{D^2}$$

where

P_f is the calculated minimum failure pressure, in kPa;

D_{LR} is the nominal weight of roof plate plus any attached structural, in N.

In USC units:

$$P_f = 1.6\ P - \frac{0.147\ D_{LR}}{D^2}$$

where

P_f is the calculated minimum failure pressure, in inches of water;

D_{LR} is the nominal weight of roof plate plus any attached structural, in lbf.

NOTE Experience with actual failures indicates that buckling of the roof-to-shell junction is localized and probably occurs when the yield point of the material is exceeded in the compression area.

F.8 Mechanically-anchored Tanks with Design Pressures up to 18 kPa (2.5 psi) Gauge

• **F.8.1** The design of the mechanical anchorage and its attachment to the tank shall be a matter of agreement between the Manufacturer and the Purchaser and shall meet the requirements of 5.12.

F.8.2 The counterbalancing weight, in addition to the requirements in 5.12, shall be designed so that the resistance to uplift at the bottom of the shell will be the greater of the following.

a) The uplift produced by 1.5 times the design pressure of the corroded empty tank plus the uplift from the design wind velocity on the tank.

b) The uplift produced by 1.25 times the test pressure applied to the empty tank (with the nominal thicknesses).

F.8.3 After the tank is filled with water, the shell and the anchorage shall be visually inspected for tightness. Air pressure of 1.25 times the design pressure shall be applied to the tank filled with water to the design liquid height. The air pressure shall be reduced to the design pressure, and the tank shall be checked for tightness. In addition, all seams above the water level shall be tested using a soap film or another material suitable for the detection of leaks. After the test water has been emptied from the tank (and the tank is at atmospheric pressure), the anchorage shall be checked for tightness. The design air pressure shall then be applied to the tank for a final check of the anchorage.