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.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^2) 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.^{2}) 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 shall be calculated using Yield Strength (F_y) and Modulus of Elasticity (E) at the maximum design temperature. Refer to Table M.1a and Table M.1b for corrections to be applied to Yield Strength (F_y) and Table M.2a and Table M.2b for values of Modulus of Elasticity (E) at maximum design temperature.

M.3.7 In the roof-to-shell-joint area calculation per 5.10.5.2, the allowable stress F_a shall be calculated using 0.6 x Yield Strength (F_y) (least) at maximum design temperature. Refer to Table M.1a and Table M.1b for corrections to be applied to Yield Strength (F_y) at maximum design temperature.

M.3.8 In E.6.2.4, the modification of the basic allowable membrane stress is stated in M.3.2. For the maximum allowable hoop tension membrane stress determined by 0.9F_y times the joint efficiency, F_y, shall be multiplied by the applicable reduction factor given in Table M.1a and Table M.1b.

Table M.1a—Yield Strength Reduction Factors (SI)

Temperature (°C)	Minimum Specified Yield Strength (MPa)		
	< 310 MPa	From ≥ 310 to < 380 MPa	≥ 380 MPa
94	0.91	0.88	0.92
150	0.88	0.81	0.87
200	0.85	0.75	0.83
260	0.80	0.70	0.79
NOTE Linear interpolation shall be applied for intermediate values.			

Table M.1b—Yield Strength Reduction Factors (USC)

Temperature (°F)	Minimum Specified Yield Strength (lbf/in.^{2})		
	< 45,000 lbf/in.^{2}	≥ 45,000 to < 55,000 lbf/in.^{2}	≥ 55,000 lbf/in.^{2}
201	0.91	0.88	0.92
300	0.88	0.81	0.87
400	0.85	0.75	0.83
500	0.80	0.70	0.79
NOTE Linear interpolation shall be applied for intermediate values.			

M.4 Tank Bottoms

M.4.1 Tanks with diameters exceeding 30 m (100 ft) shall have butt-welded annular bottom plates (see 5.1.5.6).

M.4.2 The following simplified procedure is offered as a recommended design practice for elevated-temperature tanks where significant temperature differences between the tank bottom and the lowest shell course are expected. The use of the procedure is not intended to be mandatory. It is recognized that other analytical procedures can be employed as well as that operating conditions may preclude the need for such a procedure.

Shell-to-bottom junctions in elevated-temperature tanks may be evaluated for liquid head and temperature cycles with the formulas, procedures, and exclusions given below. (See Conditions a and b in the note below, which exclude tanks from such analyses.)

NOTE A cyclic design life evaluation need not be made if all the criteria of either of the following conditions are met.

a) The design temperature difference (T) is less than or equal to 220 °C (400 °F), K is less than or equal to 2.0, and C is less than or equal to 0.5.

b) A heated liquid head, in feet, greater than or equal to $0.3(Dt)^{0.5}$ is normally maintained in the tank, except for an occasional cool-down (about once a year) to ambient temperatures; T is less than or equal to 260 °C (500 °F); and K is less than or equal to 4.0. (For background information on the development of the stress formulas, design life criteria, and C and B factors, see G.G. Karcher, "Stresses at the Shell-to-Bottom Junction of Elevated-Temperature Tanks.")

In SI units:

$$N = \left(\frac{9.7 \times 10^3}{KS}\right)^{2.44}$$

(If N is greater than or equal to 1300, cycling at the shell-to-bottom junction is not a controlling factor.)

where

N is the number of design liquid level and temperature cycles estimated for the tank design life (usually less than 1300). This design procedure contains a conservative safety margin. It is not necessary to monitor actual in-service temperature and liquid head cycles;

K is the stress concentration factor for the bottom plate at the toe of the inside shell-to-bottom fillet weld:

= 4.0 for shell-to-bottom fillet welds and lap-welded bottom plates;

= 2.0 for butt-welded annular plates where the shell-to-bottom fillet welds have been examined by 100% magnetic particle examination (see 8.2). This magnetic particle examination shall be performed on the root pass at every 13 mm of deposited weld metal while the weld is being made and on the completed weld. The examination shall be performed before hydrostatic testing:

$$S = \frac{0.028 D^2 t_b^{0.25}}{t} \times \left[\frac{58HG}{(Dt)^{0.5}} + \frac{26.2CTt^{0.5}}{D^{1.5}} - \frac{4.8B_f S_y t_b^2}{(Dt)^{1.5}} - G\right]$$

= one-half the maximum stress range that occurs in the annular plate at the shell-to-bottom junction weld, in MPa. The H and CT terms must be large enough to cause a positive S. A negative S indicates that loading conditions are not sufficient to satisfy the development assumptions of this formula. Specifically stated, the following inequality must be satisfied when the equation for S is used:

$$\left[\frac{58HG}{(Dt)^{0.5}} + \frac{26.2CTt^{0.5}}{D^{1.5}} - G\right] > \frac{4.8B_f S_y t_b^2}{(Dt)^{1.5}}$$

When the equation for S is used, the shell thickness t must be greater than or equal to the annular-plate thickness tb;

T is the difference between the minimum ambient temperature and the maximum design temperature, in °C;

S_y is the specified minimum yield strength of the bottom plate at the maximum design temperature, in MPa;

D is the nominal tank diameter, in m;

H is the difference in filling height between the full level and the low level, in m;

G is the design specific gravity of the liquid;

t is the nominal thickness of the tank's bottom shell course, in mm;

t_b is the nominal thickness of the annular bottom plate, in mm;

• C is the factor to account for radial restraint of the tank's shell-to-bottom junction with respect to free thermal expansion (C_{max} = 1.0; C_{min} = 0.25). The actual design value of C shall be established considering the tank's operating and warm-up procedure and heat transfer to the subgrade [23]:

= 0.85 if no C factor is specified by the Purchaser;

B_f is the foundation factor:

= 2.0 for tanks on earth foundations;

= 4.0 for tanks on earth foundations with a concrete ringwall.

In USC units:

$$N = \left(\frac{1.4 \times 10^6}{KS}\right)^{2.44}$$

(If N is greater than or equal to 1300, cycling at the shell-to-bottom junction is not a controlling factor.)

where

N is the number of design liquid level and temperature cycles estimated for the tank design life (usually less than 1300). This design procedure contains a conservative safety margin. It is not necessary to monitor actual in-service temperature and liquid head cycles;

K is the stress concentration factor for the bottom plate at the toe of the inside shell-to-bottom fillet weld:

= 4.0 for shell-to-bottom fillet welds and lap-welded bottom plates;

= 2.0 for butt-welded annular plates where the shell-to-bottom fillet welds have been examined by 100 % magnetic particle examination (see 8.2). This magnetic particle examination shall be performed on the root pass at every $^1/_2$ in. of deposited weld metal while the weld is being made and on the completed weld. The examination shall be performed before hydrostatic testing:

$$S = \frac{0.033 D^2 t_b^{0.25}}{t} \times \left[\frac{6.3HG}{(Dt)^{0.5}} + \frac{436CTt^{0.5}}{D^{1.5}} - \frac{B_f S_y t_b^2}{(Dt)^{1.5}} - G\right]$$

= one-half the maximum stress range that occurs in the annular plate at the shell-to-bottom junction weld, in pounds per square inch. The H and CT terms must be large enough to cause a positive S. A negative S indicates that loading conditions are not sufficient to satisfy the development assumptions of this formula. Specifically stated, the following inequality must be satisfied when the equation for S is used:

$$\left[\frac{6.3HG}{(Dt)^{0.5}} + \frac{436CTt^{0.5}}{D^{1.5}} - G\right] > \frac{B_f S_y t_b^2}{(Dt)^{1.5}}$$

[23] G. G. Karcher, "Stresses at the Shell-to-Bottom Junction of Elevated-Temperature Tanks," *1981 Proceedings—Refining Department*, Volume 60, American Petroleum Institute, Washington D.C. 1981, pp. 154 – 159.

When the equation for S is used, the shell thickness t must be greater than or equal to the annular-plate thickness tb;

T is the difference between the minimum ambient temperature and the maximum design temperature, in °F;

S_y is the specified minimum yield strength of the bottom plate at the maximum design temperature, in lbf/in.^{2};

D is the nominal tank diameter, in ft;

H is the difference in filling height between the full level and the low level, in ft;

G is the design specific gravity of the liquid;

t is the nominal thickness of the tank's bottom shell course, in inches;

t_b is the nominal thickness of the annular bottom plate, in inches;

C is the factor to account for radial restraint of the tank's shell-to-bottom junction with respect to free thermal expansion (C_{max} = 1.0; C_{min} = 0.25). The actual design value of C shall be established considering the tank's operating and warm-up procedure and heat transfer to the subgrade [29]:

= 0.85 if no C factor is specified by the Purchaser;

B_f is the foundation factor [29]:

= 2.0 for tanks on earth foundations;

= 4.0 for tanks on earth foundations with a concrete ringwall.

M.5 Self-Supporting Roofs

Table M.2a and Table M.2b shall be used to determine the material's modulus of elasticity at the maximum operating temperature.

M.6 Wind Girders

In the equation for the maximum height of unstiffened shell in 5.9.6.1, the maximum height (H_1) shall be reduced by the ratio of the material's modulus of elasticity at the maximum design temperature to 199,000 MPa (28,800,000 lbf/in.^{2}) when the ratio is less than 1.0 (see Table M.2a and Table M.2b for modulus of elasticity values).

Table M.2a—Modulus of Elasticity at the Maximum Design Temperature (SI)

Maximum Design Temperature	Modulus of Elasticity
°C	MPa
93	199,000
150	195,000
200	191,000
260	188,000
NOTE Linear interpolation shall be applied for intermediate values.	

Table M.2b—Modulus of Elasticity at the Maximum Design Temperature (USC)

Maximum Design Temperature	Modulus of Elasticity
°F	lbf/in.^{2}
200	28,800,000
300	28,300,000
400	27,700,000
500	27,300,000

NOTE Linear interpolation shall be applied for intermediate values.