Annex V
(normative)

Design of Storage Tanks for External Pressure

• V.1 Scope

This Annex provides minimum requirements that may be specified by the Purchaser for tanks that are designed for external pressure (vacuum) loading. This Annex applies to tanks for which the design external pressure exceeds 0.25 kPa (1 in. of water) but does not exceed 6.9 kPa (1.0 lbf/in.^{2}). This Annex applies to tanks subject to uniform external pressure. The requirements in this Annex represent accepted practice for application to flat-bottom tanks. However, the Purchaser may specify other procedures or additional requirements. Any deviation from the requirements of this Annex must be by agreement between the Purchaser and the Manufacturer.

V.2 General

The design procedures presented in this Annex are intended to allow the user to evaluate the design of the bottom, shell, and fixed roof of tanks for a specified design external pressure. See 5.2.2 for requirements for combining external pressure loads with other design loads. The requirements of this Annex are not intended to supersede the requirements of other Annexes of this standard that may be specified. For Annex M, S, SC, and X tanks, the variables in the equations prescribed in this Annex shall be modified in accordance with the requirements of Annex M, Annex S, Annex SC, and Annex X, respectively.

V.3 Nomenclature and Definitions

V.3.1 Nomenclature

θ is the angle between a horizontal plane and the surface of the roof plate, in degrees;

A_{reqd} is the total required cross-sectional area of the stiffener region, in mm^2 (in.^{2});

A_{stiff} is the required cross-sectional area of stiffener, mm^2 (in.^{2}) Note: A_{stiff} must be at least $^1/_2 \times A_{\mathrm{total}}$;

D is the nominal tank diameter, in m (ft);

D_L is the dead load, the weight of the tank or tank component calculated using nominal thickness unless otherwise specified, in kPa (lb/ft^2);

E is the modulus of elasticity of the roof plate material, in MPa, (lb/in.^{2});

f is the smallest of the allowable tensile stresses of the roof plate material, shell plate material, or stiffener ring material at the maximum operating temperature, in MPa (lb/in.^{2});

f_c is the smallest of the allowable compressive stresses of the roof plate material, shell plate material, bottom plate material, or stiffener ring material at the maximum operating temperature, in MPa (lb/in.^{2}). $f_c = 0.4F_y$ of components considered for the intermediate and bottom stiffener regions. However, for carbon steel, f_c need not be less than 103 MPa (15,000 lb/in.^{2}). $f_c = 0.6F_y$ of components considered for the top end stiffener region. However, for carbon steel, f_c need not be less than 140 MPa (20,000 lb/in.^{2}).

F_{pe} is a modifier for the design external pressure when used in load combinations with other variable loads. Value equals normal operating external pressure/design external pressure or a minimum of 0.4. Manufacturer to use 0.4 when not specified. (See 5.2.2.)

F_y is the yield strength of the component at the maximum operating temperature, in MPa (lb/in.^{2});

G_{in} is the unit weight of liquid inside tank, in kg/m^3 (lb/ ft^3);

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

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

$h_1, h_2 \ldots h_n$ 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 cm^4 (in.^{4});

I_{reqd} is the required moment of inertia of the stiffener ring, in cm^4 (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, kPa (lb/ft^2) = 1.0kPa (20 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 design external pressure, in kPa (lb/ft^2);

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

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

ψ is the stability factor (see V.8.1 for values);

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

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

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

S is the design balanced specified snow load (S_b), in kPa (lb/ft^2);

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

t is the nominal shell thickness, mm (in.);

t_b is the nominal thickness of bottom plate under the shell, in mm (in.);

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

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

$t_{s1}, t_{s2} \ldots t_{sn}$ is the nominal thickness of cylindrical shell course 1, 2…n, in mm (in.), where the subscript numbering is from top to bottom of the shell;

NOTE The subscript 1 denotes the top shell course and *n* denotes the lowest shell course;

t_{shell} is the nominal thickness of shell at level under consideration, in mm (in.);

t_{smin} is the nominal thickness of thinnest shell course, in mm (in.);

V_1 is the radial load imposed on the stiffener by the shell, in N/m (lb/in.);

V_{s1} is the radial pressure load imposed on the stiffener from the shell for sizing the stiffener attachment weld, in N/m (lb/ft);

v_s is the radial shear load on stiffener for sizing the stiffener attachment weld, in N (lb);

V_{s2} is the weld shear flow load imposed for sizing the stiffener attachment weld, in N/m (lb/ft);

P_{WV} is the maximum wind pressure consistent with the specified design wind velocity, in kPa (lb/ft^2). The maximum wind pressure shall be calculated as follows (see 5.9.6.1, Note 2):

In SI units:

P_{WV} is the maximum wind pressure = $1.48\left(\frac{V}{190}\right)^2$ in (kPa) where design wind speed (V) is used.

In USC units:

P_{WV} is the maximum wind pressure = $31\left(\frac{V}{120}\right)^2$ in (lbf/ft^2) where design wind speed (V) is used.

where

• V is the specified design wind velocity (3-sec gust), in kph (mph);

W_{bott} is the weight of bottom plate, in kg/m^2 (lb/ft^2);

w_{shell} is the contributing width of shell on each side of intermediate stiffener, in mm (in.);

X_{btm} is the length of bottom plate within tension/compression ring region, in mm (in.). X_{btm} = 16 t_b;

X_{cone} is the length of cone roof within tension/compression ring region, in mm (in.);

X_{dome} is the length of umbrella or dome roof within tension/compression ring region, in mm (in.);

X_{shell} is the length of shell within tension/compression ring region, in mm (in.).

V.3.2 Definitions

V.3.2.1
specified design external pressure (P_e)
Design external pressure specified on the tank data sheet (see Annex L) by the Purchaser. This specified value excludes any external pressure due to wind.

V.3.2.2
total design external pressure for the roof (P_r)
Sum of the specified design external pressure and the roof live load or snow load and the dead load as provided in V.7.1.

V.3.2.3
total design external pressure for the shell (P_s)
Sum of the specified design external pressure and the external pressure due to wind as combined in V.8.1.2.

V.4 Construction Tolerances

The procedures prescribed in this Annex are only valid for tanks that satisfy the construction tolerances of 7.5.

• V.5 Corrosion Allowance

Unless specified otherwise by the Purchaser, the evaluation of tanks in accordance with the requirements of this Annex may be based on the nominal thickness of the pressure-resisting components. If the nature of the tank service conditions is such that corrosion will result in a uniform loss of thickness of the affected components, the Purchaser should specify that corrosion allowance be deducted from the nominal thickness used in the evaluation.

• V.6 Testing

Testing of the tank design for external pressure is not required by this Annex, but may be performed if specified by the Purchaser.

V.7 Fixed Roof

The total design external pressure loading, P_r, on the roof is determined by the following equation:

$$P_r = \text{the greater of } D_L + (L_r \text{ or } S) + F_{pe} P_e \text{ or } D_L + P_e + 0.4\ (L_r \text{ or } S)$$

V.7.1 Column-Supported Cone Roof

Column-supported cone roofs may be used on tanks designed for external pressure, providing the design and construction satisfy the following requirements.

• **V.7.1.1** The roof plate spanning between support rafters may be designed as a simple beam spanning several supports, or as a catenary beam spanning between supports, or as a diaphragm, by agreement between the Purchaser and the Manufacturer. Regardless of the design method selected, the following considerations shall be addressed in the design:

a) allowable stress for both membrane and bending;

b) joint efficiency of welds joining the roof plates together;

c) assumed end fixity conditions for plate (beam) span;

d) allowable deflection criteria.

If the roof plate is designed as a catenary beam, the following additional considerations shall be addressed in the design.

e) Possibility of stress reversal and fatigue loading of welds at and between supports of the roof plate.

V.7.1.2 Additional guidance on the design of supported cone roof plates for pressure loading may be found in Reference 8 and Reference 9, for example, and in other published texts.

V.7.2 Self-Supporting Cone Roof

V.7.2.1 The required thickness of the roof plate is determined by the following equation. However, the thickness shall not be less than that required by 5.10.5.1.

In SI units:

$$t_{\text{cone}} = \frac{83D}{\sin\theta}\sqrt{\frac{P_r}{1.72E}}$$

In USC units:

$$t_{\text{cone}} = \frac{D}{\sin\theta}\sqrt{\frac{P_r}{0.248E}}$$

V.7.2.2 The total required cross-sectional area in the cone roof-to-shell joint region for external pressure on the roof is determined by the following equation.

In SI units:

$$A_{\text{reqd}} = \frac{125P_rD^2}{f\tan\theta}$$

In USC units:

$$A_{\text{reqd}} = \frac{P_rD^2}{8\ f\tan\theta}$$

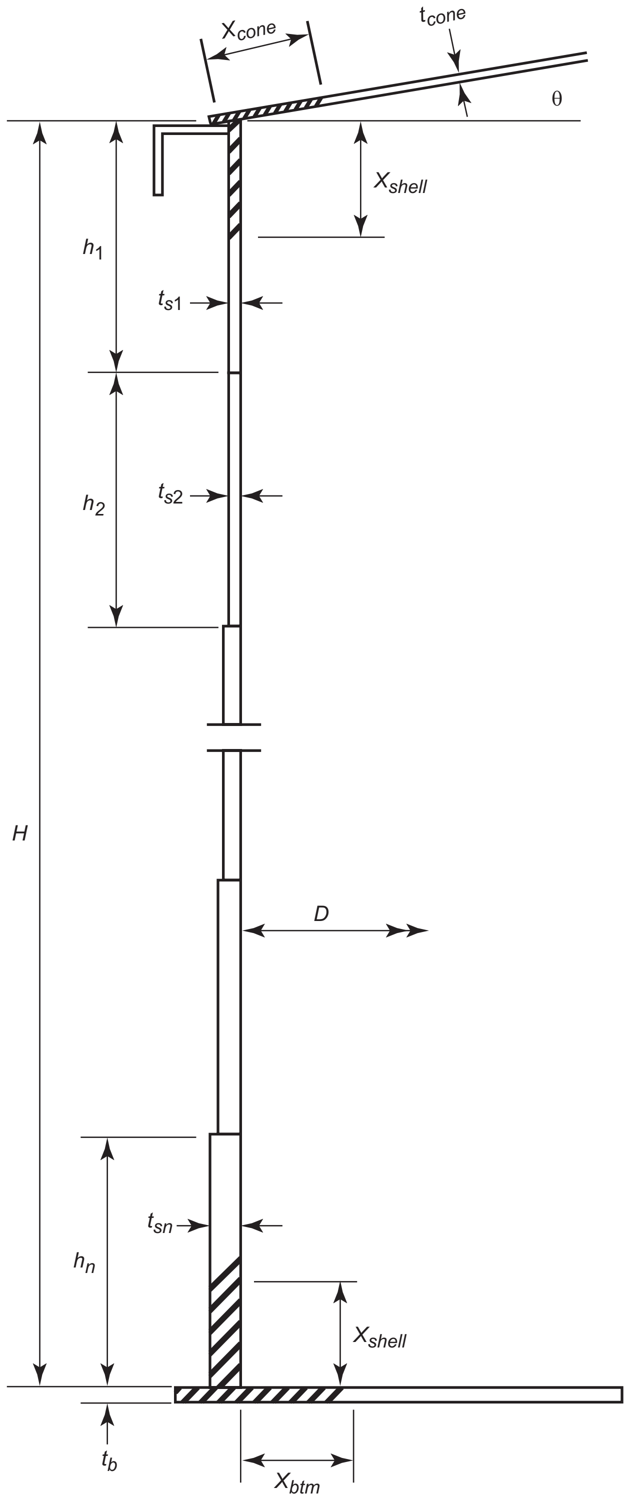
V.7.2.3 The length of cone roof considered to be within the top tension/compression ring region is determined by the following equation (see Figure V.1a):

In SI units:

$$X_{\text{cone}} = 13.4\sqrt{\frac{Dt_{\text{cone}}}{\sin\theta}}$$

In USC units:

$$X_{\text{cone}} = 1.47\sqrt{\frac{Dt_{\text{cone}}}{\sin\theta}}$$



NOTE See Annex F, Figure F.2 for alternative configurations and associated limitations on structural section used for top stiffener.

Figure V.1a—Dimensions for Self-Supporting Cone Roof

V.7.2.4 The vertical dimension measured from the top of the shell or top angle considered to be within the tension/ compression ring region is determined by the following equation (see Figure V.1a):

In SI units:

For the top tension/compression region:

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

For the bottom tension/compression region:

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

In USC units:

For the top tension/compression region:

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

For the bottom tension/compression region:

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

V.7.2.5 The required cross-sectional area of the top stiffener structural shape is determined by the following equation:

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

V.7.3 Self-Supporting Dome or Umbrella Roof

V.7.3.1 The required thickness of the roof plate is determined by the following equations. However, the thickness shall not be less than that required by 5.10.6.1. (Note that design in accordance with API 620 is permitted for dished dome roofs meeting the requirements of API 620, 5.10.5.1.)

In SI units:

$$t_{\text{dome}} = 141R\sqrt{\frac{P_r}{E}} \text{ (for umbrella and dome roofs)}$$

In USC units:

$$t_{\text{dome}} = 4.47R\sqrt{\frac{P_r}{E}} \text{ (for umbrella and dome roofs)}$$

V.7.3.2 The total required cross-sectional area in the dome or umbrella roof-to-shell joint region for external pressure on the roof is determined by the following equation. However, the area shall not be less than that required by 5.10.6.2.

In SI units:

$$A_{\text{reqd}} = \frac{300P_rRD}{f}$$

In USC units:

$$A_{\text{reqd}} = \frac{P_rRD}{3.375f}$$

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:

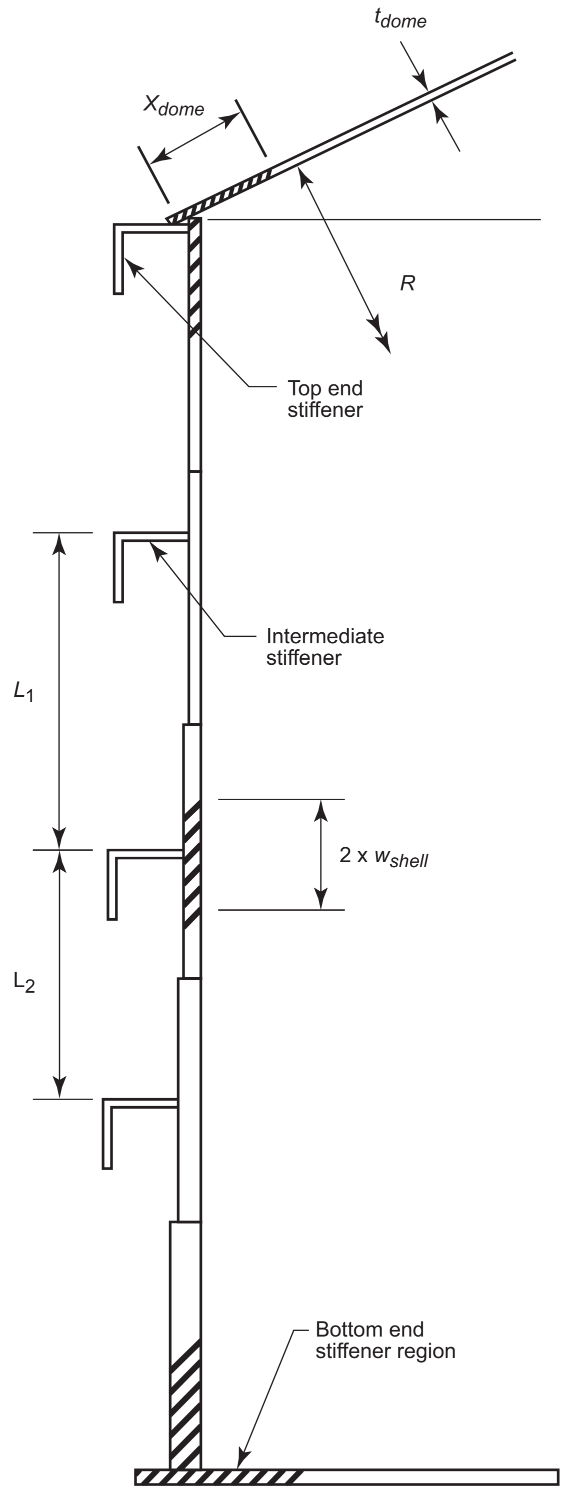
$$A_{\text{stiff}} = A_{\text{reqd}} - t_{s1}X_{\text{shell}} - t_{\text{dome}}X_{\text{dome}}$$

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, ψ, that is dependent upon the magnitude of the design external 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 design external pressure, and 2) for design external pressure alone. Each condition shall be checked using the appropriate stability factor, ψ, as follows.



NOTE See Annex F, Figure F.2 for alternative configurations and associated limitations on structural section used for top stiffener.

Figure V.1b—Dimensions for Self-Supporting Dome Roof

In SI Units:

Condition 1—Wind plus specified design external pressure

ψ = 1.0 for wind plus design external pressure [when design external pressure (P_e) is less than or equal to 0.25 kPa]. For this case, Annex V is not mandatory.

ψ = [P_e + 0.70]/0.95 for wind plus design external pressure [when design external pressure (P_e) is greater than 0.25 kPa, but less than or equal to 0.70 kPa].

ψ = [P_e/0.48] for wind plus design external pressure [when design external pressure (P_e) is greater than 0.70 kPa; however, ψ need not exceed 2.5].

Condition 2—Specified design external pressure only

ψ = 3.0

In USC Units:

Condition 1—Wind plus specified design external pressure

14 ψ = 1.0 for wind plus design external pressure [when design external pressure (P_e) is less than or equal to 5.2 psf]. For this case, Annex V is not mandatory.

ψ = [P_e + 15]/20 for wind plus design external pressure [when design external pressure (P_e) is greater than 5.2 psf, but less than or equal to 15 psf].

ψ = [P_e/10] for wind plus design external pressure [when design external pressure (P_e) is greater than 15 psf; however, ψ need not exceed 2.5].

Condition 2—Specified design external pressure only

ψ = 3.0

V.8.1.1 For an unstiffened tank shell subjected to external pressure sufficient to cause buckling, buckling will occur elastically if the following criterion (see note below) is satisfied. Note that this criterion will typically be satisfied except for very small, exceptionally thick tanks. If this criterion is not satisfied, external pressure effects should be evaluated in accordance with the requirements of the ASME *Boiler and Pressure Vessel Code*, Section VIII, Division 1.

NOTE 1 Source is The Structural Research Council (SSRC) text, "Guide to Stability Design Criteria for Metal Structures," Section 14.3.5.

In SI units:

$$\left(\frac{D}{t_{s\min}}\right)^{0.75}\left[\left(\frac{H_{TS}}{D}\right)\left(\frac{F_y}{E}\right)^{0.5}\right] \geq 0.00675$$

In USC units:

$$\left(\frac{D}{t_{s\min}}\right)^{0.75}\left[\left(\frac{H_{TS}}{D}\right)\left(\frac{F_y}{E}\right)^{0.5}\right] \geq 0.19$$

The equations in the following sections are applicable, providing the shell satisfies the criterion of this section.

V.8.1.2 The total design external pressure for the shell (P_s, using the appropriate ψ from V.8.1) and the specified design external pressure (P_e, using ψ = 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:

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

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.

V.8.1.5 End stiffeners shall be provided for unstiffened shells and shall satisfy the design requirements of V.8.2.3.

V.8.2 Circumferentially Stiffened Shells

Tank shells may be strengthened with circumferential stiffeners to increase the resistance to buckling under external pressure loading. When circumferential stiffeners are used to strengthen the cylindrical shell to resist buckling due to external pressure, the design of the stiffeners shall meet the following requirements.

V.8.2.1 Number and Spacing of Intermediate Stiffener Rings

V.8.2.1.1 Calculate the transformed shell height in accordance with V.8.1.4. (See V.10 for a numerical example of the calculation of the transformed shell height.)

V.8.2.1.2 Calculate the maximum spacing of intermediate stiffeners. The equation in V.8.1.3 can be rearranged to solve for a "safe height" of shell, H_{safe}, as follows. H_{safe} is the maximum height of unstiffened shell permitted, based on the transformed shell thickness (t_{s1}).

In SI units:

$$H_{\text{safe}} = \frac{(t_{s\min})^{2.5}(E)}{15{,}203D^{1.5}(P_s)\psi}$$

In USC units:

$$H_{\text{safe}} = \frac{0.6(t_{s\min})^{2.5}(E)}{D^{1.5}(P_s)\psi}$$

V.8.2.1.3 Calculate the number of intermediate stiffeners required, N_s, based on H_{safe}, in accordance with the following equation. A zero or negative value of N_s means that no intermediate stiffeners are required. Round up the calculated value of N_s to the nearest integer for use in subsequent calculations.

$$N_s + 1 = \frac{H_{TS}}{H_{\text{Safe}}}$$

V.8.2.1.4 Maximum stiffener spacing for each shell thickness shall be:

$$L_X = H_{\text{Safe}}\left[\frac{t_{sx}}{t_{s\min}}\right]^{2.5}$$

where

L_x is the stiffener spacing for a given shell thickness;

t_{sx} is the thickness of the shell in question.

V.8.2.2 Intermediate Stiffener Ring Design

V.8.2.2.1 The number of waves, N, into which a shell will theoretically buckle under uniform external pressure is determined in accordance with the following equation:

In SI units:

$$N^2 = \sqrt{\frac{445D^3}{t_{s\min}H_{TS}^2}} \le 100$$

In USC units:

$$N^2 = \sqrt{\frac{5.33D^3}{t_{s\min}H_{TS}^2}} \le 100$$

For design purposes, the minimum value of N is 2 and the maximum value of N is 10. Use the same N^2 for intermediate and end stiffeners.

V.8.2.2.2 The distance between adjacent intermediate stiffeners on the actual shell for shells of non-uniform thickness is determined in accordance with the following procedures.

a) Maximum spacing, L_s, on minimum shell thickness, $t_{s\min}$, = $\mathrm{H_{Safe}}$.

b) Maximum spacing, L_s on other shell thicknesses = $(\mathrm{H_{Safe}})(\mathrm{t_{sx}}/\mathrm{t_{smin}})^{2.5}$, where t_{sx} is the individual shell thickness.

c) Where the spacing between stiffeners includes different shell thicknesses, adjust the actual spacing using the transformed shell spacings adjusted accordingly. See V.10 for a numerical example of this procedure.

V.8.2.2.3 The radial load imposed on the stiffener by the shell is determined in accordance with the following equation:

In SI units:

$$Q = 1000P_sL_s$$

In USC units:

$$Q = \frac{P_sL_s}{12}$$

The stiffener should be located at $H_{TS} / (N_s + 1)$ spacing where N_s is number of intermediate stiffeners on the transformed shell.

V.8.2.2.4 The actual moment of inertia of the intermediate stiffener region, I_{act} shall be greater than or equal to the total required moment of inertia of this region, I_{reqd}, where:

I_{act} is the actual moment of inertia of the intermediate stiffener ring region, consisting of the combined moment of inertia of the intermediate stiffener and the shell within a contributing distance on each side of the intermediate stiffener. The contributing distance is determined in accordance with the following equation:

In SI units:

$w_{\mathrm{shell}} = 13.4\sqrt{Dt_{\mathrm{shell}}}$ on each side of stiffener

In USC units:

$w_{\mathrm{shell}} = 1.47\sqrt{Dt_{\mathrm{shell}}}$ on each side of stiffener where

t_{shell} is the actual thickness of the shell plate on which the stiffener is located.

V.8.2.2.5 The required moment of inertia of the intermediate stiffener region, I_{reqd} is determined in accordance with the following equation:

In SI units

$$I_{\text{reqd}} = \frac{37.5QD^3}{E(N^2 - 1)}$$

In USC units:

$$I_{\text{reqd}} = \frac{648QD^3}{E(N^2 - 1)}$$

V.8.2.2.6 In addition to the moment of inertia requirements stated above, the intermediate stiffener region shall satisfy the following area requirements.

V.8.2.2.6.1 The total required cross-sectional area of the intermediate stiffener region, A_{reqd}, is determined in accordance with the following equation:

In SI units:

$$A_{\text{reqd}} = \frac{QD}{2f_c}$$

In USC units:

$$A_{\text{reqd}} = \frac{6QD}{f_c}$$

V.8.2.2.6.2 The required cross-sectional area of the intermediate stiffener structural shape alone, A_{stiff}, is determined in accordance with the following equation:

In SI units:

$$A_{\text{stiff}} = A_{\text{reqd}} - 26.84t_{\text{shell}}\sqrt{Dt_{\text{shell}}}$$

In USC units:

$$A_{\text{stiff}} = A_{\text{reqd}} - 2.94t_{\text{shell}}\sqrt{Dt_{\text{shell}}}$$

A_{stiff} (actual) must be greater than or equal to A_{stiff} required.

A_{stiff} (actual) must also be greater than or equal to 0.5 A_{reqd}.

V.8.2.3 End Stiffeners

The actual moment of inertia of the end stiffener region, I_{act} must be greater than or equal to the total required moment of inertia of this region, I_{reqd}, where:

I_{act} is the actual moment of inertia of the end stiffener ring region, consisting of the combined moment of inertia of the end stiffener and the shell within a contributing distance on one side of the end stiffener. No credit shall be taken for the roof portion in this region, however credit may be taken for a portion of the bottom plate. The width of bottom plate considered effective as an end stiffener shall be not more than 16t_b, where t_b is the thickness of the bottom or annular plates, unless a detailed stress analysis demonstrates that a greater width may be used. The contributing distance on one side of the stiffener is determined in accordance with the following equation:

In SI units:

For the top end stiffener:

$$w_{\text{shell}} = 13.4\sqrt{Dt_{sl}}$$

For the bottom end stiffener:

$$w_{\text{shell}} = 13.4\sqrt{Dt_{sn}}$$

In USC units:

For the top end stiffener:

$$w_{\text{shell}} = 1.47\sqrt{Dt_{sl}}$$

For the bottom end stiffener:

$$w_{\text{shell}} = 1.47\sqrt{Dt_{sn}}$$

V.8.2.3.1 The radial load imposed on the end stiffener by the shell is determined in accordance with the following equation:

In SI units:

$$V_1 = 250P_sH$$

In USC units:

$$V_1 = \frac{P_sH}{48}$$

V.8.2.3.2 The required moment of inertia of the end stiffener region, I_{reqd} is determined in accordance with the following equation:

In SI units

$$I_{\text{reqd}} = \frac{37.5V_1D^3}{E(N^2-1)}$$

In USC units:

$$I_{\text{reqd}} = \frac{648V_1D^3}{E(N^2-1)}$$

V.8.2.3.3 In addition to the moment of inertia requirements stated above, the end stiffener region shall satisfy the following area requirements.

V.8.2.3.3.1 The total required cross-sectional area of the end stiffener region, A_{reqd}, is determined in accordance with the following equation:

In SI units:

$$A_{\text{reqd}} = \frac{V_1 D}{2f}$$

In USC units:

$$A_{\text{reqd}} = \frac{6V_1 D}{f}$$

V.8.2.3.3.2 The required cross-sectional area of the end stiffener structural shape alone, A_{stiff}, is determined in accordance with the following equation:

For cone roof top end stiffener:

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

For dome or umbrella roof top end stiffener:

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

For bottom end stiffener:

$$A_{\text{stiff}} = A_{\text{reqd}} - t_b X_{\text{btm}} - t_{sn} X_{\text{shell}}$$

A_{stiff} (actual) must be greater than or equal to A_{stiff} (required).

V.8.2.4 Strength of Stiffener Attachment Weld

Stiffening ring attachment welds shall be sized to resist the full radial pressure load from the shell between stiffeners, and shear loads acting radially across the stiffener caused by external design loads carried by the stiffener (if any) and a computed radial shear equal to 2 % of the stiffening ring's compressive load.

V.8.2.4.1 The radial pressure load from the shell shall be determined in accordance with the following formula:

In SI units:

$$V_{s1} = 1000\ P_s L_s$$

In USC units:

$$V_{s1} = P_s L_s$$

V.8.2.4.2 The radial shear load shall be determined in accordance with the following formula:

In SI units:

$$v_s = 10\ P_s L_s D$$

In USC units:

$$v_s = 0.01\ P_s L_s D$$

V.8.2.4.3 The weld shear flow due to the radial shear load shall be determined in accordance with the following formula:

In SI units:

$$V_{s2} = 100\ v_s q_s / I_{act}$$

In USC units:

$$V_{s2} = 12\ v_s q_s / I_{act}$$

where

q_s is the first moment of area of the stiffener.

V.8.2.4.4 The combined load for the design of the weld shall be determined in accordance with the following formula:

$$W_w = (V_{s1}{}^2 + V_{s2}{}^2)^{1/2}$$

V.8.2.4.5 The minimum fillet weld leg size shall be the smallest of the shell thickness at the location of the stiffener, the stiffener thickness at the weld location, or 6 mm (1/4 in.).

V.8.2.5 Lateral Bracing of Stiffener

The projecting part of a stiffening ring without an outer vertical flange need not be braced if the width of the projecting part in a radial vertical plane does not exceed 16 times its thickness. When this condition is not satisfied, the stiffening ring shall be laterally braced in accordance with the requirements of API 620, 5.12.5.8.

V.9 Bottom

• **V.9.1** The bottom of the tank shall be evaluated for external pressure loading if either of the following conditions is applicable. These conditions do not need to be considered simultaneously unless specified by the Purchaser.

1) If the total design external pressure force on the bottom plate exceeds the sum of the weight of the bottom plates plus the weight of any product required by the Purchaser to remain in the tank when external pressure is acting, membrane stresses in the bottom must be evaluated.

2) If the area around the tank will be subject to flooding with liquid, provisions should be included in the design of the tank and its operating procedures to ensure that the tank contains sufficient liquid to counteract bottom uplift resulting from external flooding conditions. If the tank cannot be filled with liquid of sufficient depth to counteract the uplift from the liquid pressure under the bottom of the tank, membrane stresses in the bottom must be evaluated.

V.9.2 In both of the above cases, the bottom may be evaluated as a membrane subjected to uniform loading and restrained by the compression ring characteristics of the bottom-to-shell junction. For column-supported roofs, the design of the columns shall consider the additional axial loading due to external pressure.

V.9.3 The following provisions apply when Condition 2 in V.9.1 exists.

V.9.3.1 Calculation of external (flooding) pressure:

The calculation of the hydrostatic external pressure due to flooding is performed using the equation:

$$P = G_{\text{out}} H$$

Rule 1:

When flooding of the area surrounding a tank is possible, the most effective way to prevent damage to the shell or bottom is to maintain an equivalent or higher level of liquid inside the tank whenever flooding occurs. The required minimum level of liquid to be maintained inside the tank is calculated as follows:

$$(G_{\text{in}} \text{ x } H_{\text{in}}) + W_{\text{bott}} \ / \ (\text{p x } R^2) \ ^3\ G_{\text{out}} \times H_{\text{out}}$$

Rule 2:

When it is not possible to satisfy the equation in Rule 1, the tank and anchorage, if used, shall be designed to safely resist the unbalanced pressure resulting from flood liquid. As a minimum, the following components shall be evaluated:

• **V.9.3.2 allowable stress:** Unless otherwise specified, the flooding described above may be considered a temporary loading and the allowable stress increased accordingly. However, the increase in allowable stress shall not exceed 33 % of the basic allowable stress for the subject component when evaluating the component for flood loading.

V.9.3.3 anchorage: For tanks that are mechanically anchored, the anchorage devices shall be adequate to resist the uplift and shear forces resulting from the pressure due to external flood liquid. If the tank is not mechanically anchored, provisions should be made to guide the tank back into its original position when the flooding conditions recede.

V.9.3.4 attached piping and sump: Piping and other components connecting the tank to the ground or another structure shall be capable of withstanding, without damage or failure, loads and movements due to any unbalanced pressures resulting from flooding of the area around the tank. If a sump is used, the design of the sump shall consider the possibility of the sump floating out of its pit during a flooding event.

V.9.3.5 bottom plate: Under the pressure of external flood liquid without counterbalancing internal liquid, the bottom plate will tend to deform or "balloon" upwards. As the bottom deforms and is subject to additional unbalanced pressure, membrane stresses increase in the bottom plate. The bottom plate shall be capable of withstanding this deformation without overstress of the plate or the attaching welds.

V.9.3.6 corner joint: As the bottom plate deforms upwards, compressive stresses and bending stresses in the shell-to-bottom joint increase. The shell plate and bottom plate components of the shell-to-bottom joint within the effective compression ring limits shall be proportioned to maintain combined stresses within the yield strength corresponding to the weaker of the two components.

V.10 Example Calculations

The following example calculations illustrate, in US Customary units, the use of this Annex.

V.10.1 Data

Tank diameter = 75 ft-0 in.

Tank shell height = 48 ft-0 in.

Design liquid level = 48 ft-0 in.

Design specific gravity of liquid = 1.0

Allowable design stress, S_d = 23,200 lb/in.^{2}

Allowable stress in tension ring, f = 21,600 lb/in.^{2}

Minimum yield strength of all steel = 36,000 lb/in.^{2}

Specified corrosion allowance = None

Tank bottom plate thickness = $^3/_8$ in.

Design external pressure = 0.6 lb/in.^{2}g (86.4 lb/ft^2)

Design wind velocity (3-sec gust) = 120 mph (Maximum wind pressure, P_{WV} = 31 lb/ft^2)

Design snow load = 0 lb/ft^2

Roof design live load = 25 lb/ft^2

Modulus of Elasticity, E = 30,000,000 lb/in.^{2}

Shell course heights and thicknesses calculated by the one-foot method are as follows:

Course Number	$(H-1)$ (ft)	Required Thickness (in.)	Minimum Thickness (in.)
1	7	0.059	$^5/_{16}$*
2	15	0.126	$^5/_{16}$*
3	23	0.193	$^5/_{16}$*
4	31	0.261	$^5/_{16}$*
5	39	0.328	0.328
6	47	0.395	0.395

* The thicknesses of the upper four shell courses were increased from those required for hydrostatic pressure to eliminate need for an intermediate wind girder.

V.10.2 External Pressure Calculations

1) Select roof type: Try a self-supporting cone roof with a 20-degree slope from horizontal.

From V.7,

P_r = The greater of $D_L + (L_r \text{ or } S) + F_{pe} P_e$ or $D_L + P_e + 0.4\ (L_r \text{ or } S)$,

where:

D_L = 20.4 lb/ft^2 (Estimated assuming $^1/_2$–ιν. roof plate),

L_r = 25 lb/ft^2,

S = 0 lb/ft^2,

F_{pe} = 0.4,,

P_e = 0.6 lb/in.^{2} = 86.4 lb/ft^2,

P_r = $D_L + (L_r \text{ or } S) + F_{pe} P_e$ = 20.4 + 25 + 0.4 (86.4) = 80.0 lb/ft^2, or,

P_r = $D_L + P_e + (L_r \text{ or } S)$ = 20.4 + 86.4 + 0.4 (25) = 116.8 lb/ft^2 (Governs).

The required nominal thickness of the cone roof plate is calculated from V.7.2.1, as follows:

$$t_{\text{cone}} = \frac{D}{\sin\phi}\sqrt{\frac{P_r}{0.248E}}$$

$$t_{\text{cone}} = \frac{75}{0.342}\sqrt{\frac{116.8}{7{,}440{,}000}}$$

$t_{\text{cone}} = 0.869$ in., this thickness is not practical. Consider a supported cone roof or a self-supporting dome roof.

Try a lap-welded dome roof with a dish radius of 1.0 × D = 1.0 × 75 = 75 ft. Assuming the plate weight does not change significantly, the required thickness of the dome plate is calculated from V.7.3.1 as follows:

$$t_{\text{dome}} = 4.47R\sqrt{\frac{P_r}{E}}$$

$$t_{\text{dome}} = 4.47(75)\sqrt{\frac{116.8}{30{,}000{,}000}}$$

$t_{\text{dome}} = 0.661$ in., this thickness is not practical for lap-welding.

Consider a butt-welded dome roof with a dish radius of 0.8 × D = 0.8 × 75 = 60 ft-0 in. Again assuming the plate weight does not change significantly, the required thickness of the dome plate is calculated from V.7.3.1 as follows:

$$t_{\text{dome}} = 4.47R\sqrt{\frac{P_r}{E}}$$

$$t_{\text{dome}} = 4.47(60)\sqrt{\frac{116.8}{30{,}000{,}000}}$$

$t_{\text{dome}} = 0.529$ in., this thickness is practical for butt-welding. (Alternatively, a supported cone roof could be used.)

2) Calculate the roof tension ring area required at the junction of the roof and cylindrical shell:

From V.7.3.2, the required tension ring area is calculated as follows:

$$A_{\text{reqd}} = \frac{P_r RD}{3.375f}$$

$$A_{\text{reqd}} = \frac{116.8(60)(75)}{3.375(21{,}600)}$$

$A_{\text{reqd}} = 7.21$ sq. in.

From V.7.3.3, the length of effective roof plate contributing to the tension ring area is calculated as follows:

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

$$X_{\text{dome}} = 2.1\sqrt{60(0.529)}$$

$X_{\text{dome}} = 11.83$ in.

From V.7.3.4, the length of effective shell plate contributing to the tension ring area is calculated as follows:

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

$$X_{\text{shell}} = 1.47\sqrt{75(0.3125)}$$

$X_{\text{shell}} = 7.12$ in. (Note: This value should be recalculated, if necessary, after selection of final shell thickness.)

From V.7.3.5, the required area of the stiffener is calculated as follows:

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

$$A_{\text{stiff}} = 7.21 - (0.3125)(7.21) - (0.529)(11.7)$$

$A_{\text{stiff}} = -1.23$ sq. in., Stiffener is not required

Note: This value should be recalculated, if necessary, after selection of final shell thickness.)

3) Check that buckling will occur elastically in the unstiffened cylindrical shell:

From V.8.1.1, elastic buckling will occur if the following equation is satisfied:

$$\left(\frac{D}{t_{s\min}}\right)^{0.75}\left[\left(\frac{H_{TS}}{D}\right)\left(\frac{F_y}{E}\right)^{0.5}\right] \geq 0.00675$$

$\left(\frac{75}{0.3125}\right)^{0.75}\left[\left(\frac{43.54}{75}\right)\left(\frac{36}{30{,}000}\right)^{0.5}\right] = 1.23 \geq 0.19$, thus buckling will be elastic.

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

4) Calculate the minimum shell thickness required for the combined loading from design external pressure and wind:

From V.8.1.3, the required minimum shell thickness is calculated as follows:

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

where

P_s is the greater of 1) the specified design external pressure excluding wind or 2) $W + F_{pe} P_e$, where P_{WV} is the specified design wind pressure, lb/ft^2;

P_s = P_e or ($W + F_{pe} P_e$) = 86.4 lb/ft^2 or [31 + 0.4(86.4)] = 86.4 lb/ft^2.

$$t_{s\min} \geq \frac{1.23(3 \times 43.54 \times 86.4)^{0.4}\ 75^{0.6}}{(30{,}000{,}000)^{0.4}} = 1.35 \text{ in.}$$

$$t_{s\min} \geq 0.698 \text{ in.}$$

$$\psi = 3.0$$

5) Calculate the transformed shell height:

Course Number	Actual Shell Course Height (ft)	Thickness (in.)	Transformed Shell Course Height * (ft)
1	8	0.3125	8.00
2	8	0.3125	8.00
3	8	0.3125	8.00
4	8	0.3125	8.00
5	8	0.328	7.09
6	8	0.395	4.45
Sum =	48 ft	Sum =	43.54 ft
* For example, the transformed height of No. 5 shell course = $(0.3125/.328)^{2.5}(8)$ = 7.09 ft (see V.8.1.4.b)			

The required minimum thickness is greater than the available thickness and the shell must be stiffened.

6) Calculate the maximum spacing of intermediate stiffeners:

From V.8.2.1.2,

$$H_{Safe} = \frac{0.6(t_{s\min})^{2.5}(E)}{\psi D^{1.5}(P_s)}$$

$$H_{Safe} = \frac{0.6(0.3125)^{2.5}(30{,}000{,}000)}{3(75)^{1.5}(86.4)}$$

$H_{Safe} = 5.84$ ft

7) Calculate the number of intermediate stiffeners required, N_s, based on H_{Safe}:

From V.8.2.1.3,

$N_s + 1 = H_{TS} / H_{Safe}$

$N_s + 1 = 43.54 / 5.84 = 7.46$

$N_s = 7$

Transposed spacing for 7 equally spaced stiffeners = 43.54 / 8 = 5.44 ft

8) Calculate the intermediate stiffener spacing for the non-uniform shell thickness:

From V.8.2.2.2,

Intermediate stiffener spacing on 0.3125-in. shell plate is,

$L_s = H_{Safe} = 5.84$ ft

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

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

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

$L_s = [5.84](0.395/0.3125)^{2.5} = 10.49$ 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 3rd stiffener (location = 5.44 ft × 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 6th stiffener as follows:

Available 0.3125-in. shell plate = (4 × 8 ft) – (5 × 5.75 ft) = 3.25 ft

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

6th 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

Location of 6th stiffener = 32 + 1.5 = 33.5 ft from top of tank

Locate the 7th stiffener as follows:

Available 0.328-in. shell = (5 × 8) – 33.5 = 6.5 ft

Maximum spacing on 0.328-in. shell = L_s = 6.59 ft

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

Location of 7th stiffener = 33.5 + 5.75 = 39.25 ft

Check the remaining unstiffened shell:

Difference between actual and transformed shell height = 48 – 43.54 = 4.45 ft

Length of 0.328-in. shell below stiffener = 40 – 39.25 = 0.75 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_{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_{avg} = 0.395 in.

H_{safe} is then calculated as follows:

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

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

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

The number of stiffeners required is:

$N_s + 1 = 48 / 10.48 = 4.58; N_s = 4$

Actual spacing for 4 stiffeners = 48 / 5 = 9.6 ft

10) Calculate the number of buckling waves:

From V.8.2.2.1,

$$N^2 = \sqrt{\frac{5.33D^3}{t_{s\min}L_s^2}} \leq 100;\ L_s = (L_1 + L_2)/2 = (9.6 + 9.6)/2 = 9.6\text{ft}$$

$$N^2 = \sqrt{\frac{5.33(75)^3}{(0.395)(9.6)^2}} = 249 > 100;\ N = > 10\text{, therefore use } 10$$

11) Calculate the radial load on a circumferential stiffener placed 9.6 ft from the top of the shell.

From V.8.2.2.3, the radial load is calculated as follows:

$$Q = \frac{P_s L_s}{12}\text{; where } P_s = 86.4 \text{ lb/ft}^2$$

$$Q = \frac{(86.4)(9.6)}{12} = 69.1 \text{ lb/in.}$$

12) Calculate the total contributing shell width acting with the intermediate stiffener:

From V.8.2.2.4,

$$2 \times w_{\text{shell}} = 2 \times 1.47\sqrt{Dt_{\text{shell}}}\text{; where } t_{shell} = 0.395 \text{ in.}$$

$$2 \times 1.47\sqrt{(75)(0.395)}\text{; } 16.0 \text{ in.}$$

13) Calculate the required moment of inertia of the intermediate stiffener region:

From V.8.2.2.5, the required moment of inertia is calculated as follows:

$$I_{\text{reqd}} = \frac{648QD^3}{E(N^2 - 1)}$$

$$I_{\text{reqd}} = \frac{648(69.1)(75)^3}{30{,}000{,}000(100 - 1)}$$

$$I_{\text{reqd}} = 6.36 \text{ in.}^4$$

14) Calculate the total area required in the intermediate stiffener region:

From V.8.2.2.6.1, the required area is calculated as follows:

$$A_{\text{reqd}} = \frac{6QD}{f}$$

$$A_{\text{reqd}} = \frac{6(69.1)(75)}{(14,400)}$$

$$A_{\text{reqd}} = 2.16 \text{ in.}^2$$

15) Calculate the required area of the stiffener section:

From V.8.2.2.6.2, the required area is calculated as follows:

$$A_{\text{stiff}} = A_{\text{reqd}} - 2.94 t_{\text{shell}} \sqrt{D t_{\text{shell}}}$$

$$A_{\text{stiff}} = 2.16 - 2.94(0.395)\sqrt{(75)(0.395)}$$

$A_{\text{stiff}} = -4.2$ in.^{2}; the stiffener section area must be ≥ 1.08 sq. in. ($= {}^1/_2 \times A_{\text{reqd}}$)

Select a rolled section that will satisfy the area and inertia requirements. By inspection, since the stiffener spacing is constant, the section selected is adequate for all 4 stiffeners.

16) Calculate the required properties of the top stiffener:

From V.8.2.3, the contributing distance of the cylindrical shell is calculated as follows:

$$W_{\text{shell}} = 1.47\sqrt{D t_{s1}}$$

$$W_{\text{shell}} = 1.47\sqrt{(75)(0.395)}$$

$$W_{\text{shell}} = 8.0 \text{ in.}$$

From V.8.2.3.1, the radial load on the top stiffener is calculated as follows:

$$V_1 = \frac{P_s H}{48}$$

$$V_1 = \frac{86.4(48)}{48}$$

$$V_1 = 86.4 \text{ lb/in.}$$

From V.8.2.3.2, the required moment of inertia of the top stiffener is calculated as follows:

$$I_{\text{reqd}} = \frac{684 V_1 D^3}{E(N^2 - 1)}$$

$$I_{\text{reqd}} = \frac{684(86.4)(75)^3}{30{,}000{,}000(99)}$$

$$I_{\text{reqd}} = 8.39 \text{ in.}^4$$

From V.8.2.3.3.1, the required area of the top stiffener region is calculated as follows:

$$A_{\text{reqd}} = \frac{6 V_1 D}{f}$$

$$A_{\text{reqd}} = \frac{6(86.4)(75)}{21{,}600}$$

$$A_{\text{reqd}} = 1.80 \text{ sq. in.}$$

From **V.8.2.3.3.2**, the required area of the top stiffener section is calculated as follows:

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

$$A_{\text{stiff}} = 1.80 - (0.395)(8.0) - (0.529)(11.7) = -7.55 \text{ in.}$$

The stiffener section area must be ≥ 0.90 sq. in. (= $^1/_2 \times A_{\text{total}}$)

Select a rolled section that will satisfy the area and inertia requirements.

17) Calculate the required properties of the bottom stiffener region:

From V.8.2.3, the contributing distance of the cylindrical shell is calculated as follows:

$$W_{\text{shell}} = 1.47\sqrt{D t_{sn}}$$

$$W_{\text{shell}} = 1.47\sqrt{(75)(0.395)}$$

$$W_{\text{shell}} = 8.0 \text{ in.}$$

From V.8.2.3.2, the required moment of inertia of the bottom stiffener is calculated as follows:

$$I_{\text{reqd}} = \frac{684 V_1 D^3}{E(N^2 - 1)}$$

$$I_{\text{reqd}} = \frac{684(86.4)(75)^3}{30{,}000{,}000(99)}$$

$$I_{\text{reqd}} = 8.39 \text{ in.}^4$$

From V.8.2.3.3.1, the required area of the bottom stiffener region is calculated as follows:

$$A_{\text{reqd}} = \frac{6V_1D}{f}$$

$$A_{\text{reqd}} = \frac{6(86.4)(75)}{21{,}600}$$

$$A_{\text{reqd}} = 1.80 \text{ sq. in.}$$

From V.8.2.3.3.2, the required area of the bottom stiffener section is calculated as follows:

$$A_{\text{stiff}} = A_{\text{reqd}} - t_{sn}X_{\text{shell}} - t_bX_{\text{btm}}$$

$$A_{\text{stiff}} = 1.80 - (0.395)(8.0) - (0.375)(6.0) = -3.61 \text{ in.}$$

The contributing portion of the shell-to-bottom joint has a calculated moment of inertia of 20.2 in.^{4} and will satisfy the area and inertia requirements. Thus, an additional stiffener is not necessary.

V.11 Annex V References

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[2] API Publication, *Stability of API Standard 650 Tank Shells*, Raymund V. McGrath.

[3] The Structural Research Council (SSRC), *Guide to Stability Design Criteria for Metal Structures*, Section 14.3.5.

[4] Code Case 2286, “Alternative Rules for Determining Allowable Compressive Stresses for Cylinders, Cones, Spheres and Formed Heads,” Cases of ASME *Boiler and Pressure Vessel Code*.

[5] Welding Research Council Bulletin 406, “Proposed Rules for Determining Allowable Compressive Stresses for Cylinders, Cones, Spheres and Formed Heads,” C. D. Miller and K. Mokhtarian.

[6] American Society of Mechanical Engineers (ASME) *Boiler and Pressure Vessel Code*, Section VIII, Division 1.

[7] American Iron & Steel Institute (AISI) Publication, *Steel Plate Engineering Data, Volume 2*.

[8] ASME Paper 65-MET-15, “Theoretical and Experimental Study of Steel Panels in Which Membrane Tension is Developed,” by J. S. McDermott.

[9] Machine Design Magazine, December 9, 1976, “Stress Analysis of Pressurized Panels,” by J. A. Martinelli.