**October 10, 2003**
**Agenda Item 650-464**
**Appendix for External Pressure**
**Resp: John Lieb, TIC, lieb@tankindustry.com, FAX 630-226-0802**
**Purpose: The purpose of this item is to develop an appendix for API 650 to address external pressure considerations for API 650 tanks. The business impact of this item is beneficial in that.**

NOTE: THE FOLLOWING IS THE FOURTH DRAFT OF AN API 650 APPENDIX TO ADDRESS EXTERNAL PRESSURE CONSIDERATIONS FOR API 650 TANKS. ANY COMMENTS IN BRACKETED ITALICS ARE NOT PART OF THE PROPOSED TEXT OF THE APPENDIX AND ARE INCLUDED FOR INFORMATION PURPOSES ONLY. THIS FOURTH DRAFT INCORPORATES COMMENTS ON THE THIRD DRAFT. THIS ITEM HAS BEEN BALLOTED TWICE. CHANGES TO THE THIRD DRAFT ARE INDICATED USING MICROSOFT WORD® EDITING TOOLS AND FORMAT. REVISIONS ARE INDICATED BY VERTICAL BARS IN THE LEFT MARGIN. NEW OR REVISED WORDING IS INDICATED BY UNDERLINING. DELETED TEXT IS INDICATED IN THE BALLOONS IN THE RIGHT MARGIN. AN EXCEPTION TO THIS IS THAT THE INFORMATIONAL COMMENTS IN BRACKETS AND ITALICS INCLUDED IN THE THIRD DRAFT HAVE BEEN REMOVED BUT AND DO NOT APPEAR IN STRIKETHROUGH TEXT. ANOTHER EXCEPTION IS THAT THE NOMENCLATURE HAS BEEN REMOVED FROM INDIVIDUAL SECTIONS OF THE DOCUMENT AND COMBINED IN ONE PLACE IN SECTION V.3.1. EQUATIONS THAT HAVE BEEN REVISED ARE INDICATED BY *[revised]* IN RED ITALICS FOLLOWING THE EQUATION. ALL NEGATIVE BALLOTS RECEIVED ON THE THIRD DRAFT AS OF THE FALL 2003 REFINING MEETING HAVE BEEN RESOLVED AND ALL AFFIRMATIVE BALLOT COMMENTS HAVE BEEN ADDRESSED IN DRAFT 4A.

**ONLY THE REVISED AND EDITORIALLY CORRECTED WORDING IN THIS DRAFT IS OPEN FOR COMMENT IN THE THIRD BALLOT.**

# APPENDIX V
# DESIGN OF STORAGE TANKS FOR EXTERNAL PRESSURE

## V.1 Scope

This appendix provides minimum requirements that may be specified by the purchaser for tanks that are designed to operate with external pressure (vacuum) loading as a normal operating condition. This appendix is intended to apply to tanks for which the normal operating external pressure exceeds 0.25 kPa (0.036 lbf/in$^2$) but does not exceed 6.9 kPa (1.0 lbf/in.$^2$). This appendix is intended for use with tanks subject to uniform external pressure. The requirements in this appendix 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 appendix must be by agreement between the purchaser and the manufacturer. Refer to V.11 for a discussion of the technical basis for this appendix.

Deleted: The requirements of this appendix are not intended to supercede the requirements of other appendices of this standard that may be specified.

## V.2 General

The design procedures presented in this appendix are intended to allow the user to evaluate the design of the bottom, shell and fixed roof of tanks that operate under partial vacuum conditions. See 3.2 for requirements for combining external pressure loads with other design loads. The requirements of this appendix are not intended to supercede the requirements of other appendices of this standard that may be specified. For Appendix M and S tanks, the variables in the equations prescribed in this appendix shall be modified in accordance with the requirements of Appendices M and S, respectively.

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## V.3 Nomenclature and Definitions

### V.3.1 Nomenclature

θ = angle between a horizontal plane and the surface of the roof plate (degrees)
$A_{reqd}$ = total required cross-sectional area of the stiffener region, mm$^2$ (in$^2$)
$A_{stiff}$ = required cross-sectional area of stiffener, mm$^2$ (in$^2$) Note: $A_{stiff}$ must be at least ½ x $A_{total}$.
D = nominal tank diameter, m (ft)
$D_L$ = dead load, the weight of the tank or tank component, including any corrosion allowance unless otherwise specified, kPa (lb/ft$^2$)
E = modulus of elasticity of the roof plate material, MPa, (lb/in$^2$)

Deleted: $E_1$ = joint efficiency [From API 620, Table 3-2] ... [1]

f = smallest of the allowable tensile stresses (see Table 3-2) of the roof plate material, shell plate material or stiffener ring material at the maximum operating temperature, MPa (lb/in$^2$)

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$f_c$ = 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. Mpa (lb/in$^2$). $f_c = 0.4F_y$ of components considered for the intermediate and bottom stiffener regions. However, $f_c$ need not be less than 103.4 MPa (15,000 lb/in$^2$). $f_c = 0.6F_y$ of components considered for the top end stiffener region. However, $f_c$ need not be less than 140 MPa (20,000 lb/in$^2$).
$F_y$ = yield strength of the component at the maximum operating temperature, MPa (lb/in$^2$)

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$G_{in}$ = Unit weight of liquid inside tank, kg/m$^3$ (lb/ ft$^3$)
$G_{out}$ = Unit weight of flood liquid, kg/m$^3$ (lb/ ft$^3$) [1000 kg/m$^3$ (62.4 lb/ ft$^3$) for water]
H = shell height, m (ft)
$h_1$, $h_2$…$h_n$ = height of shell courses 1, 2, 3, through n, respectively, m (ft)
$H_{in}$ = Height or depth of liquid inside tank, m (ft)
$H_{safe}$ = maximum height of unstiffened shell permitted, based on the calculated average thickness, m (ft)
HTS = Transformed height of tank shell, m (ft)
$I_{act}$ = The actual moment of inertia of the stiffener ring region, cm$^4$ (in$^4$).
$I_{reqd}$ = required moment of inertia of the stiffener ring, cm$^4$ (in$^4$)
$JE_b$ = Joint efficiency of bottom plate. $JE_b$ = 1.0 for bottom joints
$JE_c$ = joint efficiency of compression ring. $JE_c$ = 1.0 for butt welded top angles and tension/compression rings.
$JE_r$ = joint efficiency of roof plate. $JE_r$ = 0.5 for single lap welds, 0.70 for double lap welds, and 1.0 for butt welds
$JE_s$ = joint efficiency of shell plate. $JE_s$ = 1.0 for shell with full radiography, or 0.85 with partial radiography.
$L_1$, $L_2$ = distances between adjacent intermediate stiffeners or intermediate stiffener and top of shell or bottom of shell, respectively, m (ft)
$L_r$ = minimum roof live load on horizontal projected area of the roof, kPa (lb/ft$^2$) = 1.0Kpa (20 lb/ft$^2$)
$L_s$ = ($L_1$ + $L_2$) / 2, m (ft)
N = number of waves into which a shell will buckle under external pressure
$N_s$ = Number of intermediate stiffeners
$P_e$ = specified external pressure, kPa (lb/ft$^2$)
$P_r$ = total design external pressure for design of roof, kPa (lb/ft$^2$).
$P_s$ = total design external pressure for design of shell, kPa (lb/ft$^2$). $P_s$ = the greater of 1) the specified design external pressure, $P_e$, excluding wind or 2) W+0.4$P_e$
Q = radial load imposed on the intermediate stiffener by the shell, N/m (lb/in)
$q_s$ = first moment of area of stiffener for design of stiffener attachment weld, mm$^3$ (in$^3$)
R = roof dish radius, m (ft)
S = specified snow load, kPa (lb/ft$^2$)
$S_d$ = Allowable design stress, Mpa, (lb/in$^2$)
t = shell thickness, including corrosion allowance, mm (in)
$t_{avg}$ = average nominal thickness, mm (in)
$t_b$= thickness of bottom plate under the shell, including corrosion allowance, mm (in)
$t_{cone}$ = required thickness of cone roof plate, including corrosion allowance, mm (in). (Maximum 12.5 mm (.5 in.) excl. corrosion allowance)
$t_{dome}$ = required thickness of dome roof plate, including corrosion allowance, mm (in) (Maximum 12.5 mm (.5 in.) excl. corrosion allowance)
$t_{s1}$, $t_{s2}$…$t_{sn}$ = thickness of cylindrical shell course 1, 2…n, 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.
$t_{shell}$ = actual thickness of shell at level under consideration, including corrosion allowance, mm (in)
$t_{smin}$ = minimum thickness of thinnest shell course, mm (in)

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$V_1$ = radial load imposed on the stiffener by the shell, N/m (lb/ft)
$V_{s1}$ = radial pressure load imposed on the stiffener from the shell for sizing the stiffener attachment weld, N/m (lb/ft)
$v_s$ = radial shear load on stiffener for sizing the stiffener attachment weld, N (lb)
$V_{s2}$ = weld shear flow load imposed for sizing the stiffener attachment weld, N/m (lb/ft)
W = maximum wind pressure consistent with the specified design wind velocity, kPa (lb/ft$^2$). The maximum wind pressure shall be calculated as follows:
In SI Units:
$W = 0.0000479(V)^2(K_g)(K_h)$

In US Customary Units:
$W = 0.002558(V)^2(K_g)(K_h)$

where:
V = specified design wind velocity, kph (mph)
$K_g$ = wind gust factor = 1.1
$K_h$ = wind height factor = 1.1
$W_{bott}$ = Weight of bottom plate, kg/m$^2$ (lb/ ft$^2$)
$w_{shell}$ = contributing width of shell on each side of intermediate stiffener, mm (in)
$X_{btm}$ = length of bottom plate within tension/compression ring region, mm (in). $X_{btm} = 16\ t_b$.
$X_{cone}$ = length of cone roof within tension/compression ring region, mm (in)
$X_{dome}$ = length of umbrella or dome roof within tension/compression ring region, mm (in.)
$X_{shell}$ = length of shell within tension/compression ring region, mm (in)

### V.3.2 Definitions

**Average nominal thickness**: The average as-constructed thickness of the shell.
**Total design external pressure for the roof ($P_r$)**: Sum of the specified external pressure and the roof live load or snow load and the dead load as provided in V.7.1.
**Total design external pressure for the shell (P)**: Sum of the specified external pressure and the external pressure due to wind as combined in V.8.1.2.
**Specified external pressure**: External pressure specified on the tank data sheet (See Appendix L) by the purchaser. This specified value excludes any external pressure due to wind.

### V.4 Construction Tolerances

The procedures prescribed in this appendix are only valid for tanks that satisfy the construction tolerances of Section 5.5.

### ● V.5 Corrosion Allowance

Unless specified otherwise by the purchaser, the evaluation of tanks in accordance with the requirements of this appendix may be based on the as-built thickness of the pressure-resisting components, including any specified corrosion allowance. If the nature of the tank service conditions is such that corrosion will result in a uniform loss of



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thickness of the affected components, the purchaser should specify that corrosion allowance be deducted from the as-built thickness used in the evaluation.

**● V.6 Testing**

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

**V.7 Fixed Roof**

**V.7.1 Column-Supported Cone Roof**

The roof shall be designed for the greater of the following load combinations:

1) $D_L$+($L_r$ or S) +0.4$P_e$
2) $D_L$ +$P_e$+0.4($L_r$ or S),

**V.7.2 Self-Supporting Cone Roof**

**V.7.2.1** The total design external pressure loading, $P_r$, on the roof is determined by the following equation:

$P_r$ = The greater of $D_L$+($L_r$ or S) +0.4$P_e$ or $D_L$+$P_e$+0.4($L_r$ or S),

**V.7.2.2** The required thickness of the roof plate is determined by the following equation. However, the thickness shall not be less than that required by 3.10.5.1.

In SI units:

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

In US Customary Units:

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

**V.7.2.3** 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:

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

In US Customary units:

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

**Deleted:** where:
$D_L$ = dead load, the weight of the tank or tank component, including any corrosion allowance unless otherwise specified, kPa (lb/ft$^2$)
$L_r$ = minimum roof live load on horizontal projected area of the roof, kPa (lb/ft$^2$)
● S = specified snow load, kPa (lb/ft$^2$)
● $P_e$ = specified external pressure, kPa (lb/ft$^2$)

**Deleted:** where:
$P_r$ = total design external pressure, kPa (lb/ft$^2$)
$D_L$ = dead load, the weight of the tank or tank component, including any corrosion allowance unless otherwise specified, kPa (lb/ft$^2$)
$L_r$ = minimum roof live load on horizontal projected area of the roof, kPa (lb/ft$^2$)
● S = specified snow load, kPa (lb/ft$^2$)
● $P_e$ = specified external pressure, kPa (lb/ft$^2$)

**Deleted:** where:
$t_{cone}$ = maximum 12.5 mm (.5 in.) excl. corrosion allowance
$t_{cone}$ = required thickness of cone roof plate, including corrosion allowance (mm)
θ = angle between a horizontal plane and the surface of the roof plate.
$P_r$ = total design external pressure (kPa)
E = modulus of elasticity of the roof plate material (MPa) ... [2]

**Deleted:** where:
$t_{cone}$ = required thickness of cone roof plate, including corrosion allowance, in.
θ = angle between a horizontal plane and the surface of the roof plate.
$P_r$ = total design external pressure, lb/ft$^2$
E = modulus of elasticity of the roof plate material, lb/in$^2$
D= Nominal Tank Dia. (ft.)

**Deleted:** Note that the area required for external pressure may exceed the maximum area for which the roof to shell junction may be considered frangible:

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where:
$A_{reqd}$ = total required cross-sectional area, mm$^2$
$P_r$ = total design external pressure, kPa
D = outside diameter of tank, m
f = smallest of the allowable tensile stresses of the roof plate material, shell plate material or stiffener ring material at the design temperature, MPa ... [3]

**V.7.2.4** The length of cone roof considered to be within the top tension/compression ring region is determined by the following equation:

In SI units:

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

In US Customary units:

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

**V.7.2.5** 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:

In SI units:

For the top tension/compression region:

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

For the bottom tension/compression region:

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

In US Customary units:

For the top tension/compression region:

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

For the bottom tension/compression region:

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

**V.7.2.6** The required cross-sectional area of the top stiffener structural shape is determined by the following equation:

$$A_{stiff} = A_{reqd} - JE_s t_{s1} X_{shell} - JE_r t_{cone} X_{cone}$$

### V.7.3 Self-Supporting Dome or Umbrella Roof

**V.7.3.1** The total design external pressure loading, $P_r$, on the roof is determined by the following equation:

**Deleted:** where:

$A_{reqd}$ = total required cross-sectional area, in$^2$

$P_r$ = total design external pressure, lb/ft$^2$

D = outside diameter of tank, ft

f = smallest of the allowable tensile stresses of the roof plate material, shell plate material or stiffener ring material at the design temperature, lb/in$^2$

θ = angle between a horizontal plane and the surface of the roof plate.

**Deleted:** where:

$X_{cone}$ = length of cone roof within tension/compression ring region, mm

D = outside diameter of tank, m

θ = angle between a horizontal plane and the surface of the roof plate.

$t_{cone}$ = required thickness of roof plate, including corrosion allowance, mm

**Deleted:** where:

$X_{cone}$ = length of cone roof within tension/compression ring region, in.

D = outside diameter of tank, ft

θ = angle between a horizontal plane and the surface of the roof plate.

$t_{cone}$ = required thickness of roof plate, including corrosion allowance, in

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$X_{shell}$ = length of shell within tension/compression ring region, mm

D = outside diameter of tank, m

$t_{s1}$, $t_{sn}$ = thickness of cylindrical shell, mm

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$X_{shell}$ = length of shell within tension/compression ring region, in

D = outside diameter of tank, ft

$t_{s1}$, $t_{sn}$ = thickness of cylindrical shell, in

**Deleted:** $E_1 t_{s1} X_{shell}$

**Deleted:** $E_1 t_{cone} X_{cone}$

**Deleted:** where:

$A_{stiff}$ = required cross-sectional area of stiffener, mm$^2$ (in$^2$) Note: $A_{stiff}$ must be at least ½ x $A_{total}$.

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

$E_1$ = joint efficiency [From API 620, Table 3-2]

$t_{s1}$ = thickness of top cylindrical shell course 1, mm (in)

$X_{shell}$ = length of shell within tension/compression ring region, mm (in)

$t_{cone}$ = required thickness of cone roof plate, including corrosion allowance, mm (in).

$X_{cone}$ = length of cone roof within tension/compression ring region, mm (in)

$P_r$ = The greater of $D_L$+($L_r$ or S) +0.4$P_e$ or $D_L$+$P_e$+0.4($L_r$ or S)

**V.7.3.2** The required thickness of the roof plate is determined by the following equations. However, the thickness shall not be less than that required by 3.10.6.1.

In SI units:

$$t_{dome} = 127R\sqrt{\frac{P_r}{E}} \quad \text{(for umbrella and dome roofs)}$$

In US Customary units:

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

**V.7.3.3** 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 3.10.6.2.

In SI units:

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

In US Customary units:

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

**V.7.3.4** The length of dome or umbrella roof considered to be within the top tension/compression ring region is determined by the following equation:

$$X_{dome} = 0.6\sqrt{Rt_{dome}}$$

**V.7.3.5** The length of shell considered to be within the top tension/compression ring region is determined by the following equation:

$$X_{shell} = 0.43\sqrt{Dt_{s1}}$$

**Deleted:** where:
$P_r$ = total design external pressure, kPa (lb/ft$^2$)
$D_L$ = dead load, the weight of the tank or tank component, including any corrosion allowance unless otherwise specified, kPa (lb/ft$^2$)
$L_r$ = minimum roof live load on horizontal projected area of the roof, kPa (lb/ft$^2$)
• S = specified snow load, kPa (lb/ft$^2$)
• $P_e$ = specified external pressure, kPa (lb/ft$^2$)

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$t_{dome}$ = required thickness of dome roof plate, including corrosion allowance, mm
$P_r$ = total design external pressure, kPa
E = modulus of elasticity of the roof plate material, Mpa
R = roof dish radius, m

**Deleted:** where:
$t_{dome}$ = required thickness of dome roof plate, including corrosion allowance, in
$P_r$ = total design external pressure, lb/ft$^2$
E = modulus of elasticity of the roof plate material, lb/in2
R = roof dish radius, ft

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$A_{reqd}$ = total required cross-sectional area, mm$^2$
$P_r$ = total design external pressure, kPa
R = roof dish radius, m
D = outside diameter of tank, m
f = smallest of the allowable tensile stresses of the roof plate material, shell plate material or stiffener ring material at the design temperature, MPa
θ = angle between a horizontal plane and the surface of the roof plate.

**Deleted:** where:
$A_{reqd}$ = total required cross-sectional area, in$^2$
$P_r$ = total design external pressure, lb/ft$^2$
R = roof dish radius, ft
D = outside diameter of tank, ft
f = smallest of the allowable tensile stresses of the roof plate material, shell plate material or stiffener ring material at the design temperature, lb/in$^2$ ... [4]

**Deleted:** where:
$X_{dome}$ = length of umbrella or dome roof within tension/compression ring region, mm (in)
R = roof dish radius , mm (in)
$t_{dome}$ = required thickness of roof plate, including corrosion allowance, mm (in)

**V.7.3.6** The required cross-sectional area of the top stiffener structural shape is determined by the following equation:

$$A_{stiff} = A_{reqd} - JE_s t_{s1} X_{shell} - JE_r t_{dome} X_{dome}$$

## V.8 Shell

### • V.8.1 Unstiffened Shells

The rules included herein are intended to be consistent with ASME/ANSI B96.1 except that the equations have been modified to reflect the higher modulus of elasticity for steel as compared to aluminum. The procedure utilizes the minimum thickness and the transformed shell method to establish intermediate stiffener number and locations. The equations are based on a Factor of Safety of 3.0. If a F.O.S other than 3.0 is desired, the equations in V.8.1.2 and V.8.1.3 may be modified accordingly, with the written approval of the purchaser. The equations also include a 0.8 "knockdown" factor for imperfections in the cylindrical shell geometry.

**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* 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 & Pressure Vessel Code, Section VIII, Division 1.

In SI units:

$$\left(\frac{D}{t_{smin}}\right)^{0.75}\left[\left(\frac{H_{TS}}{D}\right)\left(\frac{F_y}{E}\right)^{.5}\right] \geq 0.00228$$ ***[revised]***

In US Customary units:

$$\left(\frac{D}{t_{smin}}\right)^{0.75}\left[\left(\frac{H_{TS}}{D}\right)\left(\frac{F_y}{E}\right)^{.5}\right] \geq 0.19$$ ***[revised]***

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

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

**V.8.1.2** The design external pressure for an unstiffened tank shell shall not exceed:

In SI units:

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¶
$X_{shell}$ = length of shell within tension/compression ring region, mm (in)¶
D = outside diameter of tank, mm (in)¶
$t_{s1}$ = thickness of cylindrical shell, including corrosion allowance, mm (in) ¶
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$A_{stiff}$ = required cross-sectional area of stiffener, $mm^2$ ($in^2$)¶
$A_{reqd}$ = total required cross-sectional area, $mm^2$ ($in^2$)¶
$E_1$ = joint efficiency [From API 620, Table 3-2]¶
$t_{s1}$ = thickness of cylindrical shell, including corrosion allowance, mm (in) ¶
$X_{shell}$ = length of shell within tension/compression ring region, mm (in)¶
$t_{dome}$ = required thickness of dome roof plate, including corrosion allowance, mm (in) ¶
$X_{dome}$ = length of umbrella or dome roof within tension/compression ring region, mm (in.)¶
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D = tank diameter, m¶
t = average nominal shell thickness, including corrosion allowance, mm *[See Note in next section concerning "average"]*¶
H = shell height, m¶
$F_y$ = yield strength of the shell, MPa¶
E = modulus of elasticity of the shell, MPa¶
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D = tank diameter, ft¶
t = average nominal shell thickness, including corrosion allowance, in. *[See Note in next section concerning "average"]*¶
H = shell height, ft¶
$F_y$ = yield strength of the shell, lb/in2¶
E = modulus of elasticity of the shell, lb/in2¶
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$$P_s \le \frac{E}{45649\left(\frac{H_{TS}}{D}\right)\left(\frac{D}{t_{smin}}\right)^{2.5}}$$ ***[revised]***

In US Customary units:

$$P_s \le \frac{E}{720\left(\frac{H_{TS}}{D}\right)\left(\frac{D}{t_{smin}}\right)^{2.5}}$$ ***[revised]***

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

In SI units:

$$t_{smin} \ge \frac{73.6\left(H_{TS}P_s\right)^{0.4} D^{0.6}}{(E)^{0.4}}$$ ***[revised]***

In US Customary units:

$$t_{smin} \ge \frac{14\left(H_{TS}P_s\right)^{0.4} D^{0.6}}{(E)^{0.4}}$$ ***[revised]***

**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

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where:¶
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E = modulus of elasticity of the shell, Mpa¶
$P_s$ = the greater of 1) the specified design external pressure excluding wind or 2) W+0.4$P_e$, where W is the specified design wind pressure, kPa¶
H = shell height, m¶
D = tank diameter, m¶
t = average nominal shell thickness, mm ¶

**Deleted:** where:¶
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E = modulus of elasticity of the shell, lb/in2¶
$P_s$ = the greater of 1) the specified design external pressure excluding wind or 2) W+0.4$P_e$, where W is the specified design wind pressure, lb/in2¶
H = shell height, ft¶
D = tank diameter, ft¶
t = average nominal shell thickness, in. ¶
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$P_s$ = the greater of 1) the specified design external pressure excluding wind or 2) W+0.4$P_e$, where W is the specified design wind pressure, lb/in2 ¶
H = shell height, m¶
D = tank diameter, m¶
E = modulus of elasticity of the shell, MPa¶
t = average nominal shell thickness, including corrosion allowance, mm ¶
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¶
$P_s$ = design external pressure, lb/in$^2$¶
H = shell height, ft¶
D = tank diameter, ft¶
E = modulus of elasticity of the shell, lb/in$^2$¶
t = average nominal shell thickness, including corrosion allowance, in. ¶
¶

**Deleted:** average nominal thickness

**Deleted:** $t_{top}$

**Deleted:** , where $t_{top}$ is the thickness of the topmost shell course and $t_{act}$ is the thickness of the shell course under consideration

**Deleted:** $t_{top}$

**Deleted:** Calculate the average thickness of the tank shell

**Deleted:** where:¶
$t_{s1}$, $t_{s2}$, $t_{s3}$, $t_n$ = thickness, including corrosion allowance of shell courses 1, 2, 3, through n, respectively, mm (in) ¶
$h_1$, $h_2$, $h_3$, $h_n$ = height of shell cours ... [5]

**Deleted:** items a and b above

equivalent resistance to buckling from external pressure as a tank of the actual height with an average (uniform) thickness calculated in accordance with item c above.

### 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 calculated average thickness.

In SI Units:

$$H_{safe} = \frac{(t_{smin})^{2.5}(E)}{D^{1.5}(73.6)^{2.5}(P_s)}$$ ***[revised]***

In US Customary Units:

$$H_{safe} = \frac{(t_{smin})^{2.5}(E)}{D^{1.5}(14)^{2.5}(P_s)}$$ ***[revised]***

**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 V.8.2.1.5 and subsequent calculations.

$N_s + 1 = H_{TS} / H_{safe}$,

**V.8.2.1.4** Calculate the spacing of intermediate stiffeners in accordance with the following equation:

Spacing = $H_{TS} / (N_s + 1)$,

#### V.8.2.2 Intermediate Stiffener Ring Design

**Deleted:** **V.8.2.1.2** Calculate the average thickness available in the unstiffened shell in accordance with **V.8.1.4**,¶
¶
In SI units:¶
¶
$t_{avg} = (t_{s1}h_1 + t_{s2}h_2 + t_{s3}h_3 \ldots + t_{sn}h_n) / 1000H$¶
¶
where:¶
¶
$t_{s1}, t_{s2} \ldots t_{sn}$ = thickness of cylindrical shell course 1, 2…n, mm ¶
$h_1, h_2 \ldots h_n$ = height of shell courses 1, 2, 3, through n, respectively, mm ¶
H = shell height, m ¶
¶
In US Customary units:¶
¶
$t_{avg} = (t_{s1}h_1 + t_{s2}h_2 + t_{s3}h_3 \ldots + t_{sn}h_n) / 12H$¶
¶
where:¶
¶
$t_{s1}, t_{s2} \ldots t_{sn}$ = thickness of cylindrical shell course 1, 2…n, in¶
$h_1, h_2 \ldots h_n$ = height of shell courses 1, 2, 3, through n, respectively, in¶
H = shell height, ft ¶
. ¶

**Deleted:** 3

**Deleted:** 4

**Deleted:** :

**Deleted:** Transformed Shell Height

**Deleted:** where:¶
¶
$N_s$ = Number of intermediate stiffeners¶
Transformed Shell Height and Hsafe are as defined above¶
¶

**Deleted:** 5

**Deleted:** Transformed Shell Height

**Deleted:** where:¶
¶
Transformed Shell Height and $N_s$ are as defined above¶

**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:

$$N^2 = \sqrt{\frac{445D^3}{t_{smin} L_s^2}} \leq 100 \qquad \textit{[revised]}$$

In US Customary units:

$$N^2 = \sqrt{\frac{5.33D^3}{t_{smin} L_s^2}} \leq 100 \qquad \textit{[revised]}$$

For design purposes, the minimum value of N is 2 and the maximum value of N is 10.

**V.8.2.2.2** The radial load imposed on the stiffener by the shell is determined in accordance with the following equation:

In SI units:

$$Q = 1000 P_s L_s$$

In US Customary units:

$$Q = \frac{P_s L_s}{12}$$

This calculation is restricted to only one intermediate stiffener. Some large tanks may require more than one stiffener.

The stiffener should be located at $H/(N_s+1)$ spacing where $N_s$ is number of intermediate stiffeners.

**V.8.2.2.3** 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:

$I_{act}$ = 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:

**Deleted:** where:
N = number of waves into which a shell will buckle under external pressure
D = tank diameter, m
$t_{avg}$ = average nominal shell thickness between stiffeners, including corrosion allowance, mm
H= Half the distance from center of stiffener to the next stiffener one side plus half the distance from stiffener to next stiffener on other side, m.

**Deleted:** where:
N = number of waves into which a shell will buckle under external pressure
D = tank diameter, ft
$t_{avg}$ = average nominal shell thickness between stiffeners, including corrosion allowance, in
H= Half the distance from center of stiffener to the next stiffener one side plus half the distance from stiffener to next stiffener on other side, ft.

**Deleted:** where:
Q = radial load imposed on the stiffener by the shell, N/m
$P_s$ = combined loading from design pressure and wind, kPa
$P_s$ = the greater of 1) the specified design external pressure excluding wind or 2) W+0.4$P_e$, where W is the specified design wind pressure, kPa
$L_s = (L_1 + L_2) / 2$, where .
. $L_1$ = distance between intermediate stiffener and top of shell or intermediate stiffener above, m
. $L_2$ = distance between intermediate stiffener and bottom of shell or intermediate stiffener below, m

**Deleted:** For equal stability above and below the stiffener,

**Deleted:** t

**Deleted:** n

**Deleted:** The location of the stiffener on actual shell should be at the same course and relative position as the location of stiffener on transposed shell using thickness relationship.

**Deleted:** where:
Q = radial load imposed on the stiffener by the shell, lb/in
$P_s$ = combined loading from design pressure and wind, kPa
$P_s$ = the greater of 1) the specified design external pressure excluding wind or 2) W+0.4$P_e$, where W is the specified design wind pressure, lb/ft2
$L_s = (L_1 + L_2) / 2$, where .
... [6]

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

In US Customary units:

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

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

**V.8.2.2.4** The required moment of inertia of the intermediate stiffener region, $I_{reqd}$ is determined in accordance with the following equation:

In SI units

$$I_{reqd} = \frac{37.5QD^3}{E(N^2-1)}$$ ***[revised]***

In US Customary units:

$$I_{reqd} = \frac{648QD^3}{E(N^2-1)}$$ ***[revised]***

**V.8.2.2.5** In addition to the moment of inertia requirements stated above, the intermediate stiffener region shall satisfy the following area requirements.

**V.8.2.2.5.1** The total required cross-sectional area of the intermediate stiffener region, $A_{reqd}$, is determined in accordance with the following equation:

In SI units:

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

In US Customary units:

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

**V.8.2.2.5.2** 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:

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

Deleted: where:

D = tank diameter (m)
$t_{shell}$ = actual thickness of shell at level under consideration, including corrosion allowance, (mm)
$w_{shell}$ = contributing width of shell on each side of intermediate stiffener, (mm)

Deleted: where:

D = tank diameter (ft)
$t_{shell}$ = actual thickness of shell at level under consideration, including corrosion allowance, (in)
$w_{shell}$ = contributing width of shell on each side of intermediate stiffener, (in)

Deleted: where:

$I_{reqd}$ = required moment of inertia of the intermediate stiffener ring, $cm^4$
Q = radial load imposed on the stiffener by the shell, N/m
D = tank diameter, m
E = modulus of elasticity, MPa
N = number of waves into which a shell will buckle under external pressure

Deleted: where:

$I_{reqd}$ = required moment of inertia of the intermediate stiffener ring, $in^4$
Q = radial load imposed on the stiffener by the shell, lb/in
D = tank diameter, ft
E = modulus of elasticity, $lb/in^2$
N = number of waves into which a shell will buckle under external pressure

Deleted: where:

$A_{reqd}$ = total required cross-sectional area of the intermediate stiffener region, $mm^2$
Q = radial load imposed on the stiffener by the shell, N/m
D = tank diameter, m
f = smaller of the allowable stresses for shell and stiffening ring material, MPa

Deleted:
where:

$A_{reqd}$ = total required cross-sectional area of the intermediate stiffener region, $in^2$
Q = radial load imposed on the stiffener by the shell, lb/in
D = tank diameter, ft
f = smallest of the allowable stresses for shell, roof and stiffening ring material, $lb/in^2$

In US Customary units:

> **Deleted:** where:
>
> $A_{stiff}$ = required cross-sectional area of intermediate stiffener structural shape, $cm^2$
> $A_{reqd}$ = total required cross-sectional area of the intermediate stiffener region, $cm^2$
> $t_{shell}$ = actual thickness of shell at level under consideration, including corrosion allowance, mm
> D = tank diameter, m

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

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

> **Deleted:** where:
>
> $A_{stiff}$ = required cross-sectional area of intermediate stiffener structural shape, $in^2$
> $A_{reqd}$ = total required cross-sectional area of the intermediate stiffener region, $in^2$
> $t_{shell}$ = actual thickness of shell at level under consideration, including corrosion allowance, in
> D = tank diameter, ft

**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:

$I_{act}$ = 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 $32t_b$, 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: $w_{shell} = 13.4\sqrt{D t_{s1}}$

For the bottom end stiffener: $w_{shell} = 13.4\sqrt{D t_{sn}}$

In US Customary units:

> **Deleted:** where:
>
> D = tank diameter (m)
> $t_{s1}$ = actual thickness, including corrosion allowance, of top shell course, (mm)
> $t_{sn}$ = actual thickness, including corrosion allowance, of bottom shell course, (mm)
> $w_{shell}$ = contributing width of shell on each side of intermediate stiffener, (mm)

For the top end stiffener: $w_{shell} = 1.47\sqrt{D t_{s1}}$

For the bottom end stiffener: $w_{shell} = 1.47\sqrt{D t_{sn}}$

> **Deleted:**
> where:
>
> D = tank diameter (ft)
> $t_{s1}$ = actual thickness, including corrosion allowance, of top shell course, (in)
> $t_{sn}$ = actual thickness, including corrosion allowance, of bottom shell course, (mm)
> $w_{shell}$ = contributing width of shell on each side of intermediate stiffener, (in)

**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:

$$V_1 = 250 P_s H$$

In US Customary units:

> **Deleted:** where:
>
> $V_1$ = radial load imposed on the stiffener by the shell, N/m
> $P_s$ = combined loading from design pressure and wind, kPa
> $P_s$ = the greater of 1) the specified design external pressure excluding wind or 2) W+0.4$P_e$, where W is the specified design wind pressure, kPa
> H = tank height, m

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

**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

$$I_{reqd} = \frac{37.5V_1D^3}{E(N^2-1)}$$ ***[revised]***

In US Customary units:

$$I_{reqd} = \frac{684V_1D^3}{E(N^2-1)}$$ ***[revised]***

**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:

$$A_{reqd} = \frac{V_1D}{2f}$$

In US Customary units:

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

**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:

$$A_{stiff} = A_{reqd} - JE_rt_{cone}X_{cone} - JE_st_{s1}X_{shell}$$

For dome or umbrella roof top end stiffener:

$$A_{stiff} = A_{reqd} - JE_st_{s1}X_{shell} - JE_rt_{dome}X_{dome}$$

For bottom end stiffener:

Deleted: where:

$V_1$ = radial load imposed on the stiffener by the shell, lb/in

$P_s$ = combined loading from design pressure and wind, lb/ft$^2$

$P_s$ = the greater of 1) the specified design external pressure excluding wind or 2) W+0.4$P_e$, where W is the specified design wind pressure, kPa

H = tank height, ft

Deleted: where:

$I_{reqd}$ = required moment of inertia of the end stiffener ring, cm$^4$

$V_1$ = radial load imposed on the stiffener by the shell, N/m

D = tank diameter, m

E = modulus of elasticity, MPa

N = number of waves into which a shell will buckle under external pressure

N is determined in accordance with **V.8.2.1.1**.

Deleted: where:

$I_{reqd}$ = required moment of inertia of the end stiffener ring, in$^4$

$V_1$ = radial load imposed on the stiffener by the shell, lb/in

D = tank diameter, ft

E = modulus of elasticity, lb/in$^2$

N = number of waves into which a shell will buckle under external pressure

N is determined in accordance with **V.8.2.1.1**.

Deleted: where:

$A_{reqd}$ = total required cross-sectional area of the end stiffener region, mm$^2$

$V_1$ = radial load imposed on the stiffener by the shell, N/m

D = tank diameter, m

f = smaller of the allowable stresses for shell or stiffening ring material, MPa

Deleted: where:

$A_{reqd}$ = total required cross-sectional area of the end stiffener region, in$^2$

$V_1$ = radial load imposed on the stiffener by the shell, lb/in

D = tank diameter, ft

f = smallest of the allowable stresses for shell, roof or stiffening ring material, lb/in$^2$

$$A_{stiff} = A_{reqd} - JE_b t_b X_{btm} - JE_s t_{sn} X_{shell}$$

$A_{stiff}$ (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.

Deleted: where:

$A_{stiff}$ = required cross-sectional area of top stiffener structural shape, mm$^2$ (in$^2$)
$A_{reqd}$ = total required cross-sectional area of the top stiffener region, mm$^2$ (in$^2$)
$t_{cone}$ = thickness of cone roof, including corrosion allowance, mm $t_{dome}$ = thickness of dome or umbrella roof, including corrosion allowance, mm (in)
$t_{s1}$ = thickness of top shell course, including corrosion allowance, mm (in)
$t_{sn}$ = thickness of bottom shell course, including corrosion allowance, mm (in)
$E_1$ = joint efficiency. See API Standard 620, Table 3-2.
$X_{cone}$ = length of cone roof within tension/compression ring region, mm (in.)
$X_{shell}$ = length of shell within tension/compression ring region, mm (in)
$X_{dome}$ = length of umbrella or dome roof within tension/compression ring region, mm (in)

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

$$V_{s1} = P_s L_s$$

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

$$v_s = 0.01 P_s L_s D$$

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

$V_{s2} = v_s q_s / I_s$, 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.8.2.4.4** 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 Standard 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:

$$P = G_{out}H,$$

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:

$$(G_{in} \text{ x } H_{in}) + W_{bott}/(\pi \text{ x } R^2) \geq G_{out} \text{ x } H_{out} ,$$

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** 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 recedes.

**V.9.3.3** 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.

Deleted: where:

$G_{out}$ = Unit weight of flood liquid, kg/m$^3$ (lb/ ft$^3$) [1000 kg/m$^3$ (62.4 lb/ ft$^3$) for water]
H = Height or depth of flood liquid, m (ft)

Deleted: where:

$G_{in}$ = Unit weight of liquid inside tank, kg/m$^3$ (lb/ ft$^3$)
$H_{in}$ = Height or depth of liquid inside tank, m (ft)
$W_{bott}$ = Weight of bottom plate, kg/m$^2$ (lb/ ft$^2$)
R = Radius of tank, m (ft)
$G_{out}$ = Unit weight of flood liquid, kg/m$^3$ (lb/ ft$^3$)
$H_{out}$ = Height or depth of flood liquid (above bottom of tank), m (ft)

**V.9.3.4** Corner Joint: As the bottom plate deforms upwards, compressive stresses and bending stresses in the corner joint increase. The shell plate and bottom plate components of the corner 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.9.3.5** 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.9.3.6** 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.10 Example Calculations**

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

**V.10.1 Data**

Tank diameter = 75 ft.-0 in.
Tank shell height = 48 ft.-0 in.
Design liquid level = 48 ft.-0 in.
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 = 100 mph (Maximum wind pressure, W = 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) (feet) | Required Thickness (inches) | Minimum Thickness (inches) |
|---|---|---|---|
| 1 | 7 | .059 | 5/16* |
| 2 | 15 | .126 | 5/16* |
| 3 | 23 | .193 | 5/16* |

Deleted: 18

| | | | |
|---|---|---|---|
| 4 | 31 | .261 | 5/16* |
| 5 | 39 | .328 | .328 |
| 6 | 47 | .395 | .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.

Deleted: that

**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.7.2.1**, $P_r$ = The greater of $D_L$+($L_r$ or S) +0.4$P_e$ or $D_L$+$P_e$+0.4($L_r$ or S), where:
$D_L$ = 20.4 lb/ft$^2$ (Estimated assuming ½-inch roof plate)
$L_r$ = 25 lb/ft$^2$
S = 0 lb/ft$^2$
$P_e$ = 0.6 lb/in$^2$ = 86.4 lb/ft$^2$
$P_r$ = 20.4 + 25 + 0.4 (86.4) = 80.0 lb/ft$^2$, or
$P_r$ = 20.4 + 86.4 + 0.4 (25) = 116.8 lb/ft$^2$ (Governs)

The required thickness of the cone roof plate is calculated from **V.7.2.2**, as follows:

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

$$t_{cone} = \frac{75}{.342}\sqrt{\frac{116.8}{7{,}440{,}000}}$$

$t_{cone}$ = 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 x D = 1.0 x 75 = 75 ft. Assuming the plate weight does not change significantly, the required thickness of the dome plate is calculated from **V.7.3.2** as follows:

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

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

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

Consider a butt-welded dome roof with a dish radius of 0.8 x D = 0.8 x 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.7.3.2** as follows:

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

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

$t_{dome}$ = 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.7.3.3**, the required tension ring area is calculated as follows:

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

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

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

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

$$X_{dome} = 0.6\sqrt{Rt_{dome}}$$

$$X_{dome} = 0.6\sqrt{60(12)(0.529)}$$

$X_{dome}$ = 11.7 in.

From **V.7.3.5**, the length of effective shell plate contributing to the tension ring area is calculated as follows:

$$X_{shell} = 0.43\sqrt{Dt_{s1}}$$

$$X_{shell} = 0.43\sqrt{75(12)(0.3125)}$$

$X_{shell}$ = 7.21 in. (Note: This value should be recalculated, if necessary, after selection of final shell thickness.)

From **V.7.3.6**, the required area of the stiffener is calculated as follows:

$A_{stiff} = A_{reqd} - E_1 t_{s1} X_{shell} - E_1 t_{dome} X_{dome}$

$A_{stiff} = 7.21 - (0.85)(0.3125)(7.21) - (0.85)(0.529)(11.7)$

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$A_{stiff}$ = 0.03 sq. in., Use a stiffener with an area ≥ 0.03 sq. in. (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:

$$\left(\frac{D}{t_{smin}}\right)^{0.75}\left[\left(\frac{H_{TS}}{D}\right)\left(\frac{F_y}{E}\right)^{.5}\right] \geq 0.19$$ ***[revised]***

$$\left(\frac{75}{0.3125}\right)^{0.75}\left[\left(\frac{43.54}{75}\right)\left(\frac{36}{30{,}000}\right)^{.5}\right] = 1.23 \geq 0.19$$, thus buckling will be elastic. (Note: This value should be recalculated, if necessary, after selection of final shell thickness.)

Deleted: It is conservative to use the maximum shell thickness in the above equation, as follows:¶
¶

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

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

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$$t_{smin} \geq \frac{14(H_{TS}P_s)^{0.4} D^{0.6}}{(E)^{0.4}}$$ ***[revised]***

where:

$P_s$ = the greater of 1) the specified design external pressure excluding wind or 2) W+0.4$P_e$, where W is the specified design wind pressure, lb/ft$^2$

$P_s$ = 0.6 lb/in$^2$ = 86.4 lb/ft$^2$ or 31 + 0.4 (86.4) = 65.6 lb/ft$^2$

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$$t_{smin} \geq \frac{14(43.54(0.6))^{0.4} 75^{0.6}}{(30{,}000{,}000)^{0.4}}$$ ***[revised]***

$t_{avg}$ ≥ 0.703 in.

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5. Calculate the transformed shell height:

| Course<br>Number | Actual Shell Course Height (ft) | Thickness (in) | Transformed Shell Course Height * (ft) |
|---|---|---|---|
| 1 | 8 | .3125 | 8.00 |
| 2 | 8 | .3125 | 8.00 |
| 3 | 8 | .3125 | 8.00 |
| 4 | 8 | .3125 | 8.00 |
| 5 | 8 | .328 | 7.09 |
| 6 | 8 | .395 | 4.45 |
| Sum = | 48 ft | Sum = | 43.54 ft |

* For example, the transformed height of No. 5 shell course = $(.3125/.328)^{2.5}(8) = 7.09$ ft (Ref. 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,

$$H_{safe} = \frac{(t_{smin})^{2.5}(E)}{D^{1.5}(14)^{2.5}(P_s)}$$ ***[revised]***

Substituting values in this equation yields:

$$H_{safe} = \frac{(.3125)^{2.5}(30{,}000{,}000)}{(75)^{1.5}(733.36)(0.6)}$$ ***[revised]***

$H_{safe} = 5.73$ ft

7. Calculate the number of intermediate stiffeners required, $N_s$, based on $H_{safe}$:

From V.8.2.1.3,

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

$N_s + 1 = 43.54 / 5.73 = 7.6$

$N_s = 7$

Actual spacing for 7 stiffeners = 43.54 / 8 = 5.44 ft

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

Deleted: 6. Calculate the average thickness available in the unstiffened shell:

From **V.8.1.4.c**, the average thickness is calculated as follows:

$t_{avg} = (t_{s1}h_1 + t_{s2}h_2 + t_{s3}h_3 \ldots + t_{sn}h_n) / H$

$t_{avg} = [(.3125)(8)(4) + (8)(.328 + .395)] / 48 = 0.329$ in.

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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:

$$H_{safe} = \frac{(.395)^{2.5}(30{,}000{,}000)}{(75)^{1.5}(733.36)(0.6)}$$

$H_{safe}$ = 10.29 ft

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

**Deleted:** the transformed height of the shell

The number of stiffeners required is:

$N_s + 1 = 48 / 10.29 = 4.66$; $N_s = 4$

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

Calculate the number of buckling waves:

From V.8.2.2.1,

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

***[revised]***

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

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

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From V.8.2.2.2, the radial load is calculated as follows:

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

**Deleted:** ; $L_s = (L_1+L_2)/2 = (9.6+9.6)/2 = 9.6$ ft.

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

10. Calculate the total contributing shell width acting with the intermediate stiffener:

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From **V.8.2.2.3**, 2 x $w_{shell}$ = 2 x $1.47\sqrt{Dt_{shell}}$ ; where $t_{shell}$=0.395 in.

$2 \text{ x } 1.47\sqrt{(75)(0.395)} = 16.0$ in.

11. Calculate the required moment of inertia of the intermediate stiffener region:

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From **V.8.2.2.4**, the required moment of inertia is calculated as follows:

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

***[revised]***

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

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

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12. Calculate the total area required in the intermediate stiffener region:

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From **V.8.2.2.5.1**, the required area is calculated as follows:

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

$$A_{reqd} = \frac{6(69.1)(75)}{(21{,}600)}$$

$A_{reqd} = 1.44$ sq. in.

13. Calculate the required area of the stiffener section:

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From **V.8.2.2.5.2**, the required area is calculated as follows:

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

$$A_{stiff} = 1.44 - 2.94(.395)\sqrt{(75)(.395)}$$

$A_{stiff} = -4.9$ sq. in.; the stiffener section area must be $\geq 0.72$ sq. in. (= ½ x $A_{reqd}$)

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.

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14. Calculate the required properties of the top stiffener:

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

$$w_{shell} = 1.47\sqrt{Dt_{s1}}$$

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

$w_{shell}$ = 8.0 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 lb/in.

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

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

$$I_{reqd} = \frac{684(86.4)(75)^3}{30{,}000{,}000(99)}$$ *[revised]*

$I_{reqd}$ = 8.39 in$^4$

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

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

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

$A_{reqd}$ = 1.80 sq. in

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

$$A_{stiff} = A_{reqd} - JE_s t_{s1} X_{shell} - JE_r t_{dome} X_{dome}$$

$A_{stiff}$ = 1.80 – (0.85)(.395)(8.0) – (0.85)(0.529)(11.7) = -6.15 in. The stiffener section area must be ≥ 0.90 sq. in. (= ½ x $A_{total}$)

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

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16. 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:

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

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

$w_{shell}$ = 8.0 in.

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

$$I_{reqd} = \frac{684V_1D^3}{E(N^2-1)}$$ ***[revised]***

$$I_{reqd} = \frac{684(86.4)(75)^3}{30{,}000{,}000(99)}$$ ***[revised]***

$I_{reqd}$ = 8.39 in$^4$

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

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

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

$A_{reqd}$ = 1.80 sq. in

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

$$A_{stiff} = A_{reqd} - JE_st_{sn}X_{shell} - JE_bt_bX_{btm}$$

$A_{stiff}$ = 1.80 – (0.85)(.395)(8.0) – (0.85)(0.375)(6.0) = -2.80 in.

The corner joint comprised of a portion of the shell and the bottom plate 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.

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V.11 Technical Basis of This Appendix

The organization of this appendix was modeled after a proprietary DuPont Standard SG 11.4 S. API appreciates DuPont's consent to utilize their standard as a model without any restriction or reservation to develop this appendix. The equations prescribed in this appendix were generally extracted from the same proprietary standard and are based on the same fundamental equations from various public domain references used to develop the proprietary standard. However, where appropriate, the nomenclature was changed to be consistent with API Standard 650. Some equations have been modified from the proprietary standard to be consistent with API Standard 650 safety factors or other design considerations. For example, some equations have been modified to be consistent with Reference 2. Where necessary, equations have been added for consistency with API Standard 650 design principles, such as incorporation of the transformed shell method.

V.12 References

1. DuPont Corporate Engineering Standard SG11.4S, "Field Erected Storage Tank Design Procedures", Section 5, External Pressure Design.
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 & Pressure Vessel Code, Section VIII, Division 1.
7. American Iron & Steel Institute (AISI) Publication "Steel Plate Engineering Data, Volume 2".

*[Additional proposed changes to API 650 resulting from this agenda item: Note that new wording is shown underlined, deleted wording is shown with strikethrough.]*

In Section 1:

Update Table 1-1 to reference Appendix V, Design of Storage Tanks for External Pressure, and indicate status as Purchaser's option.

Add new section under **1.1** to read:

"**1.1.22** Appendix V provides additional requirements for tanks that are designed to operate under external pressure (vacuum) conditions."

In Section 3:

Section 3.2.4 should be revised to read:

"**3.2.4** See Appendix V for the provisions for the design of tanks subject to partial internal vacuum exceeding 0.25 kPa (1 in. of water). Tanks that meet the requirements of this standard may be subjected to a partial vacuum of 0.25 kPa (1 in. of water), without the need to provide any additional supporting calculations."

In Section 8, modify the definition of the design pressure value to appear on the tank nameplate as follows:

**8.1.1**, change item **i** to read:

"i. The design pressure, which shall be shown as atmospheric unless Appendix F or Appendix V applies. If Appendix V applies, design pressure shall be shown as a negative number. If both Appendices F and V apply, the positive and negative pressures shall be separated by a forward slash and shall be followed by consistent units of measurement.

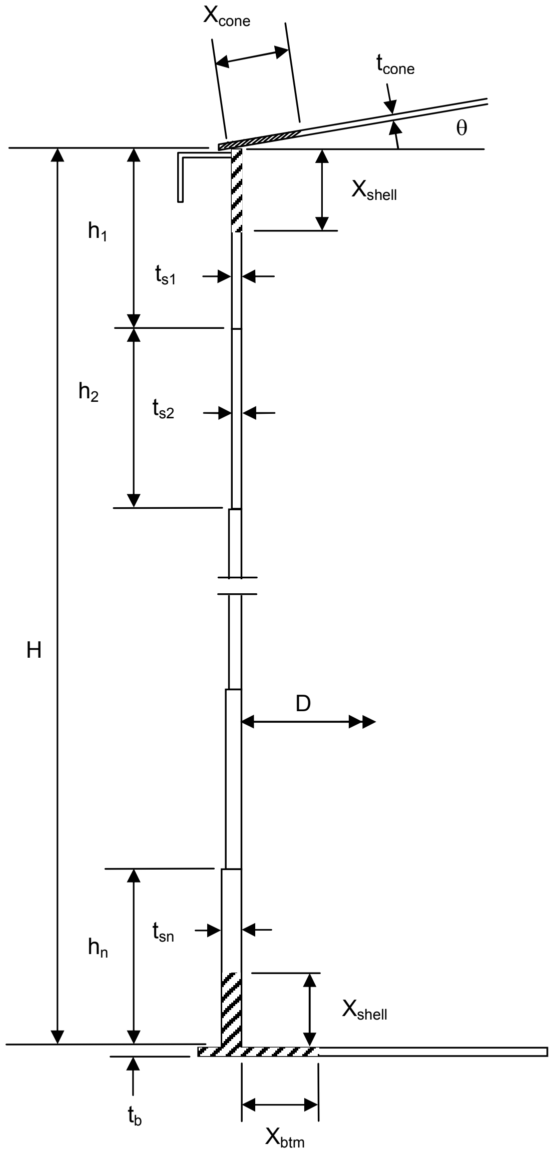


Figure 1A

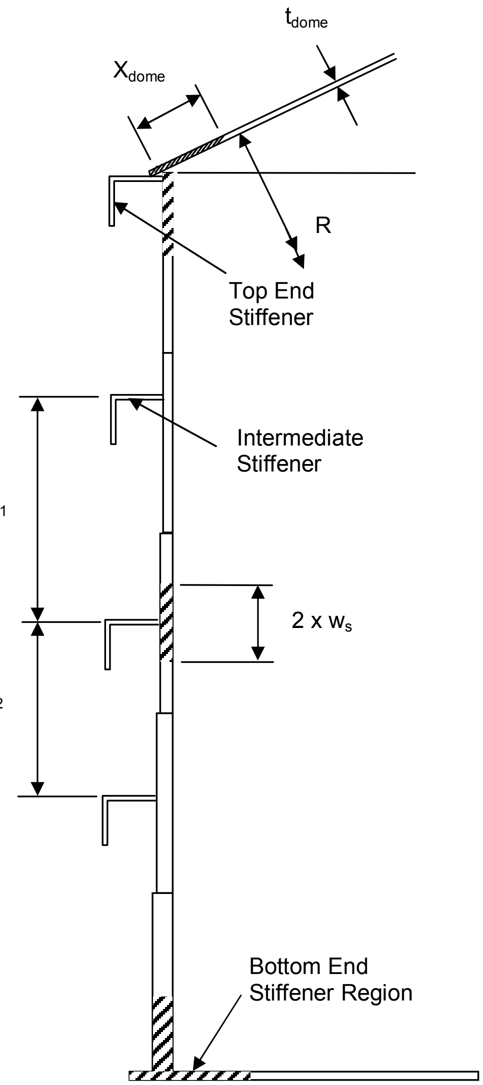


Figure 1B

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**$E_1$ = joint efficiency [From API 620, Table 3-2]**

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**where:**

**$t_{cone}$ = maximum 12.5 mm (.5 in.) excl. corrosion allowance**
**$t_{cone}$ = required thickness of cone roof plate, including corrosion allowance (mm)**
**$\theta$ = angle between a horizontal plane and the surface of the roof plate.**
**$P_r$ = total design external pressure (kPa)**
**E = modulus of elasticity of the roof plate material (MPa)**
**D= Nominal tank Dia. (m)**
**In US Customary units:**

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**where:**

**$A_{reqd}$ = total required cross-sectional area, $mm^2$**
**$P_r$ = total design external pressure, kPa**
**D = outside diameter of tank, m**
**f = smallest of the allowable tensile stresses of the roof plate material, shell plate material or stiffener ring material at the design temperature, MPa**
**$\theta$ = angle between a horizontal plane and the surface of the roof plate.**

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**where:**

**$A_{reqd}$ = total required cross-sectional area, $in^2$**
**$P_r$ = total design external pressure, $lb/ft^2$**
**R = roof dish radius, ft**
**D = outside diameter of tank, ft**
**f = smallest of the allowable tensile stresses of the roof plate material, shell plate material or stiffener ring material at the design temperature, $lb/in^2$**
**$\theta$= angle between a horizontal plane and the surface of the roof plate.**

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where:
**$t_{s1}$, $t_{s2}$, $t_{s3}$, $t_n$ = thickness, including corrosion allowance of shell courses 1, 2, 3, through n, respectively, mm (in)**
$h_1$, $h_2$, $h_3$, $h_n$ = height of shell courses 1, 2, 3, through n, respectively, mm (in)
H = total height of tank shell, mm (in)
Note: In the above subscripts, 1 denotes the top shell course and n denotes the lowest shell course.

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where:

$Q$ = radial load imposed on the stiffener by the shell, lb/in
$P_s$ = combined loading from design pressure and wind, kPa
$P_s$ = the greater of 1) the specified design external pressure excluding wind or 2) $W+0.4P_e$, where W is the specified design wind pressure, lb/ft2

$L_s = (L_1 + L_2) / 2$, where

$L_1$ = distance between intermediate stiffener and top of shell or intermediate stiffener above, ft

$L_2$ = distance between intermediate stiffener and bottom of shell or intermediate stiffener below, ft