AN INTRODUCTION TO
WELDED TANKS FOR OIL STORAGE, API STANDARD 650
(TWELFTH EDITION, JANUARY 2016)

SUMMER 2017

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SCOPE

• BOTTOM IS UNIFORMLY SUPPORTED
• TANKS IN NON-REFRIGERATED SERVICE
• MAXIMUM DESIGN TEMPERATURE OF 93 °C
• MAXIMUM DESIGN INTERNAL PressURES OF 18 KPA
• MAXIMUM DESIGN EXTERNAL PRESSURE OF 6.9 KPA

NOTE:
A bullet (•) at the beginning of a paragraph indicates that there is an expressed decision or action required of the Purchaser. The Purchaser's responsibility is not limited to these decisions or actions alone. When such decisions and actions are taken, they are to be specified in documents such as requisitions, change orders, data sheets, and drawings.
STANDARD INTRODUCTION

Pressure Vessels (ASME CODE)-Internal pressure

STORAGE TANK SCOPE OF WORK

Pressure Vessels (ASME CODE)-Vacuum Condition

1 barg

0 bar Gauge = 1 Bar a
= 14.7 Psi =~101 Kpa

-6Kpa

0 bar absolute
STANDARD INTRODUCTION

0 bar Gauge = 1 Bar a
= 14.7 Psi =~101 Kpa

1 barg

API 620

18 Kpa

API 650

-6Kpa
Type of Tanks

- Single wall
- Double wall
- Elevated tank
- Buried tank
- Rectangular tank
- Spherical tank
Type of Tanks

Single wall

- Fixed Roof
  - Self Supported
    - Structural Supported
      - Internal Floating
      - External Floating
  - Cone Roof
    - Dome Roof
    - Umbrella Roof
- Floating Roof
  - Single deck
  - Double deck
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Section 2 : Normative References
Section 3 : Terms and Definitions
Section 4 : Materials
Section 5 : Design
Section 6 : Fabrication
Section 7 : Erection
Section 8 : Methods of Examining Joints
Section 9 : Welding Procedure and Welder Qualifications
Section 10 : Marking
Annex A : Optional Design Basis for Small Tanks
Annex B : Recommendations for Design and Construction of Foundations for Aboveground Oil Storage Tanks
Annex C : External Floating Roofs
Annex D: Inquiries and Suggestions for Change
Annex E: Seismic Design of Storage Tanks
Annex F: Design of Tanks for Small Internal Pressures
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Annex V: Design of Storage Tanks for External Pressure
STORAGE TANK PARTS INTRODUCTION
MATERIAL AND IMPACT TEST
MATERIALS

- Materials used in the construction of tanks shall conform to the specifications listed in section 4, subject to the modifications and limitations indicated in API 650 standard. Material produced to specifications other than those listed in this section may be employed, provided that the material is certified to meet all of the requirements of an applicable material specification listed in API 650 standard and the material’s use is approved by the Purchaser. The Manufacturer’s proposal shall identify the material specifications to be used. Some listed materials in section 4 are as stated following:
MATERIALS

ASTM PLATES (MOST USEFUL ITEMS):

- ASTM A36M/A36 for plates to a maximum thickness of 40 mm
- ASTM A283M/A283, Grade C, for plates to a maximum thickness of 25 mm
- ASTM A285M/A285, Grade C, for plates to a maximum thickness of 25 mm
- ASTM A516M Grades 380, 415, 450, 485/A516, Grades 55, 60, 65, and 70, for plates to a maximum thickness of 40 mm (insert plates and flanges to a maximum thickness of 100 mm)
- ASTM A537M/A537, Class 1 and Class 2, for plates to a maximum thickness of 45 mm (insert plates to a maximum thickness of 100 mm)
- ASTM A573M Grades 400, 450, 485/A573, Grades 58, 65, and 70, for plates to a maximum thickness of 40 mm.
MATERIALS

ASTM SHEETS:

- ASTM A1011M, Grade 33

STRUCTURAL SHAPES

- ASTM A36M/A36
- ASTM A131M/A131
- Structural Steels listed in AISC, Manual of Steel Construction
- EN 10025, Grade S275, Qualities JR, J0, and J2
MATERIALS

✓ Piping

API Spec 5L, Grades A, B, and X42
ASTM A53M/A53, Grades A and B
ASTM A106 M/A106, Grades A and B
ASTM A333M/A333, Grades 1 and 6
ASTM A334M/A334, Grades 1 and 6
ASTM A420M/A420, Grade WPL6

✓ Forgings:

ASTM A105M/A105
ASTM A181M/A181
ASTM A350M/A350, Grades LF1 and LF2
**IMPACT TEST**

- **Toughness:** Toughness is, broadly, a measure of the amount of energy required to cause an item - a test piece or a bridge or a pressure vessel - to fracture and fail. The more energy that is required then the tougher the material. So, the ability of a material to withstand an impact blow is referred to as notch toughness.

- **Context of an impact test:** a measure of the metal's resistance to brittle or fast fracture in the presence of a flaw or notch and fast loading conditions.

- **There are two main forms of impact test,** the Izod and the Charpy test. Both involve striking a standard specimen with a controlled weight pendulum travelling at a set speed. The amount of energy absorbed in fracturing the test piece is measured and this gives an indication of the notch toughness of the test material.
These tests show that metals can be classified as being either 'brittle' or 'ductile'. A brittle metal will absorb a small amount of energy when impact tested, a tough ductile metal a large amount of energy.

The energy absorbed is the difference in height between initial and final position of the hammer. The material fractures at the notch and the structure of the cracked surface will help indicate whether it was a brittle or ductile fracture.
IMPACT TEST

Charpy

10 mm

55 mm

Absorbed energy (Joules)

 brittle fracture

lower shelf

ductile fracture

transition region

Upper shelf

 Scale

Starting position

Hammer

Anvil

Specimen

End of swing

% age crystallinity

Temperature
Impact test is NOT required

Material Curve
IMPACT TEST

Material Curve

Impact test is required

T (°C)

\( t \) (mm)
Brittle Fracture

- Failure of Liberty ships in WW II - Low-carbon steels were ductile at RT tensile tests, they became brittle when exposed to lower-temperature ocean environments. The ships were built and used in the Pacific Ocean but when they were employed in the Atlantic Ocean, which is colder, the ship's material underwent a ductile to brittle transition.
Table 4.4b—Material Groups (USC)

(See Figure 4.1b and Note 1 below.)

<table>
<thead>
<tr>
<th>Group I As Rolled, Semi-killed</th>
<th>Group II As Rolled, Killed or Semi-killed</th>
<th>Group III As Rolled, Killed Fine-Grain Practice</th>
<th>Group IIIA Normalized, Killed Fine-Grain Practice</th>
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</thead>
<tbody>
<tr>
<td>Material</td>
<td>Notes</td>
<td>Material</td>
<td>Notes</td>
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<tr>
<td>A283 C</td>
<td>2</td>
<td>A131 B</td>
<td>6</td>
</tr>
<tr>
<td>A285 C</td>
<td>2</td>
<td>A36</td>
<td>2, 5</td>
</tr>
<tr>
<td>A131 A</td>
<td>2</td>
<td>G40.21-38W</td>
<td></td>
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<tr>
<td>A36</td>
<td>2, 3</td>
<td>Grade 250</td>
<td>7</td>
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<td>Grade 235</td>
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<td>Grade 250</td>
<td>8</td>
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<tr>
<td>Grade 250</td>
<td>5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Group IV As Rolled, Killed Fine-Grain Practice</th>
<th>Group IVA As Rolled, Killed Fine-Grain Practice</th>
<th>Group V Normalized, Killed Fine-Grain Practice</th>
<th>Group VI Normalized or Quenched and Tempered, Killed Fine-Grain Practice Reduced Carbon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Notes</td>
<td>Material</td>
<td>Notes</td>
</tr>
<tr>
<td>A573-65</td>
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<td>A662 C</td>
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<tr>
<td>A573-70</td>
<td></td>
<td>A573-70</td>
<td>10</td>
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<tr>
<td>A516-65</td>
<td></td>
<td>G40.21-44W</td>
<td>8, 10</td>
</tr>
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<td>A516-70</td>
<td></td>
<td>G40.21-50W</td>
<td>8, 10</td>
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<td>A662 B</td>
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<td>E275 D</td>
<td></td>
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<tr>
<td>G40.21-44W</td>
<td>8</td>
<td>E355 D</td>
<td></td>
</tr>
<tr>
<td>G40.21-50W</td>
<td>8</td>
<td>S275 J2</td>
<td>8</td>
</tr>
<tr>
<td>E275 C</td>
<td>8</td>
<td>S355 (J2 or K2)</td>
<td>8</td>
</tr>
<tr>
<td>E355 C</td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S275 J0</td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S355 J0</td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grade 250</td>
<td>8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
IMPACT TEST

NOTES

1. Most of the listed material specification numbers refer to ASTM specifications (including Grade or Class); there are, however, some exceptions: G40.21 (including Grade) is a CSA specification; Grades E275 and E355 (including Quality) are contained in ISO 630; Grades S275 and S355 (including quality) are contained in EN10025; and Grade 235, Grade 250, and Grade 275 are related to national standards (see 4.2.6).

2. Must be semi-killed or killed.

3. Thickness $\leq 0.75$ in.

4. Deleted.

5. Manganese content shall be 0.80% to 1.2% by heat analysis for thicknesses greater than 0.75 in., except that for each reduction of 0.01% below the specified carbon maximum, an increase of 0.06% manganese above the specified maximum will be permitted up to the maximum of 1.35%. Thicknesses $\leq 0.75$ in. shall have a manganese content of 0.80% to 1.2% by heat analysis.

6. Thickness $\leq 1$ in.

7. Must be killed.

8. Must be killed and made to fine-grain practice.

9. Must be normalized.

10. Must have chemistry (heat) modified to a maximum carbon content of 0.20% and a maximum manganese content of 1.60% (see 4.2.7.4).

11. Produced by the thermo-mechanical control process (TMCP).

12. See 5.7.4.6 for tests on simulated test coupons for material used in stress-relieved assemblies.

13. See 4.2.10 for impact test requirements (each plate-as-rolled tested).
NOTE 1  The Group II and Group V lines coincide at thicknesses less than 13 mm.
NOTE 2  The Group III and Group IIIA lines coincide at thicknesses less than 13 mm.
NOTE 3  The materials in each group are listed in Table 4.4a and Table 4.4b.
NOTE 4  Deleted.
NOTE 5  Use the Group IIA and Group VIA curves for pipe and flanges (see 4.5.4.2 and 4.5.4.3).
• **DESIGN METAL TEMPERATURE:**

• The lowest temperature considered in the design, which, unless experience or special local conditions justify another assumption, shall be assumed to be 8 °C (15 °F) above the lowest one-day mean ambient temperature of the locality where the tank is to be installed. Isothermal lines of lowest one-day mean temperature are shown in Figure 4.2. The temperatures are not related to refrigerated-tank temperatures (see 1.1.1).
• **Min. Amb. Temperature : -15 °C**

<table>
<thead>
<tr>
<th>Course #</th>
<th>Material</th>
<th>Thickness (mm)</th>
<th>Impact Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A 516 70 N</td>
<td>26</td>
<td>?</td>
</tr>
<tr>
<td>2</td>
<td>A 516 70</td>
<td>26</td>
<td>?</td>
</tr>
<tr>
<td>3</td>
<td>A 516 70</td>
<td>20</td>
<td>?</td>
</tr>
<tr>
<td>4</td>
<td>A 283 C</td>
<td>20</td>
<td>?</td>
</tr>
<tr>
<td>5</td>
<td>A 283 C</td>
<td>14</td>
<td>?</td>
</tr>
<tr>
<td>6</td>
<td>A 283 C</td>
<td>10</td>
<td>?</td>
</tr>
<tr>
<td>7</td>
<td>A 283 C</td>
<td>6</td>
<td>?</td>
</tr>
</tbody>
</table>
### Example

- **Min. Amb. Temperature:** -15 °C

<table>
<thead>
<tr>
<th>Course #</th>
<th>Material</th>
<th>Thickness (mm)</th>
<th>Impact Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A 516 70 N</td>
<td>26</td>
<td>No</td>
</tr>
<tr>
<td>2</td>
<td>A 516 70</td>
<td>26</td>
<td>Yes</td>
</tr>
<tr>
<td>3</td>
<td>A 516 70</td>
<td>20</td>
<td>Yes</td>
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<tr>
<td>4</td>
<td>A 516 60</td>
<td>20</td>
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<td>5</td>
<td>A 283 C</td>
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</tr>
<tr>
<td>6</td>
<td>A 283 C</td>
<td>10</td>
<td>No</td>
</tr>
<tr>
<td>7</td>
<td>A 283 C</td>
<td>6</td>
<td>No</td>
</tr>
</tbody>
</table>
### Table 4.5a—Minimum Impact Test Requirements for Plates (SI) (See Note)

<table>
<thead>
<tr>
<th>Plate Material(^a) and Thickness ((t)) in mm</th>
<th>Thickness</th>
<th>Average Impact Value of Three Specimens(^b)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm</td>
<td>Longitudinal</td>
</tr>
<tr>
<td>Groups I, II, III, and IIIA</td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>(t \leq \text{maximum thicknesses in 4.2.2 through 4.2.5})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Groups IV, IVA, V, and VI (except quenched and tempered and TMCP)</td>
<td>(t \leq 40)</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td>(t = 45)</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>(t = 50)</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td>(t = 100)</td>
<td>68</td>
</tr>
<tr>
<td>Group VI (quenched and tempered and TMCP)</td>
<td>(t \leq 40)</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>(t = 45)</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td>(t = 50)</td>
<td>61</td>
</tr>
<tr>
<td></td>
<td>(t = 100)</td>
<td>68</td>
</tr>
</tbody>
</table>

\(^a\) See Table 4.4a.

\(^b\) Interpolation is permitted when determining minimum average impact value for plate thickness between the named thicknesses.

**NOTE** For plate ring flanges, the minimum impact test requirements for all thicknesses shall be those for \(t \leq 40\) mm.
### Research case

- As Rolled
- Semi-Killed
- Killed
- Fine-Grain Practice
- Normalized
- Quenched and Tempered
WELDING
TYPE OF JOINTS:

1. Butt joint (لب به لب)
2. Corner joint (گوشه ای)
3. T-joint (سپری)
4. Lap joint (لبه روی هم)
5. Edge joint (لبه ای)
TYPE OF GROOVE:

Butt joint

Bevel-Groove

Flare-Bevel-Groove

Flare-V-Groove

J-Groove
TYPE OF GROOVE:

Butt joint
Corner joint (گوشه ای)
T-joint (سپری)
Lap joint (لبه روی هم)
DESIGN CONSIDERATION
5.2. Design Considerations

a) Dead Load (DL): The weight of the tank or tank component, including any corrosion allowance.

b) Design External Pressure (Pe): Shall not be less than 0.25 kPa, except that Pe shall be considered as 0 kPa

c) Design Internal Pressure (Pi): Shall not exceed 18 kPa.

d) Hydrostatic Test: The load due to filling the tank with water to the design liquid level.

e) Minimum Roof Live Load: 1.0 kPa on the horizontal projected area of the roof.

h) Snow (S)

k) Wind (W)

l) External Loads
Figure 5.4—Storage Tank
5.6.2. Allowable Stress

Maximum Allowable Product Design Stress ($S_d$):

- The design stress basis, $S_d$, shall be either two-thirds the yield strength or two-fifths the tensile strength, whichever is less.

Maximum Allowable hydrostatic test Stress ($S_t$):

- The hydrostatic test basis shall be either three-fourths the yield strength or three-sevenths the tensile strength, whichever is less.
<table>
<thead>
<tr>
<th>Plate Specification</th>
<th>Grade</th>
<th>Nominal Plate Thickness $t$ (mm)</th>
<th>Minimum Yield Strength $S_y$ (MPa)</th>
<th>Minimum Tensile Strength $S_u$ (MPa)</th>
<th>Product Design Stress $S_d$ (MPa)</th>
<th>Hydrostatic Test Stress $S_t$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM Specifications</td>
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<tr>
<td>A253M</td>
<td>C</td>
<td>205</td>
<td>360</td>
<td>137</td>
<td>154</td>
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<td>A256M</td>
<td>C</td>
<td>205</td>
<td>360</td>
<td>137</td>
<td>154</td>
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</tr>
<tr>
<td>A131M</td>
<td>A, B</td>
<td>235</td>
<td>400</td>
<td>157</td>
<td>171</td>
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<tr>
<td>A38M</td>
<td></td>
<td>260</td>
<td>400</td>
<td>180</td>
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<td>A131M</td>
<td>EH 36</td>
<td>260</td>
<td>400</td>
<td>190</td>
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<td>A573M</td>
<td>400</td>
<td>220</td>
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<td>147</td>
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<td>A573M</td>
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<td>460</td>
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<tr>
<td>A573M</td>
<td>485</td>
<td>290</td>
<td>485</td>
<td>193</td>
<td>208</td>
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<tr>
<td>A516M</td>
<td>380</td>
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<td>A516M</td>
<td>415</td>
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<tr>
<td>A516M</td>
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<td>A537M</td>
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<td>$r \leq 65$</td>
<td>$65 &lt; r \leq 100$</td>
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<td>485</td>
<td>206</td>
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<td>A537M</td>
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<td>C, D</td>
<td>$r \leq 65$</td>
<td>$65 &lt; r \leq 100$</td>
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<td>485</td>
<td>208</td>
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<tr>
<td>A678M</td>
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<td>246</td>
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<td>416</td>
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<td>G40.21M</td>
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<td>G40.21M</td>
<td>260 WT</td>
<td>260</td>
<td>410</td>
<td>184</td>
<td>176</td>
<td></td>
</tr>
<tr>
<td>G40.21M</td>
<td>300W</td>
<td>300</td>
<td>400</td>
<td>190</td>
<td>193</td>
<td></td>
</tr>
<tr>
<td>G40.21M</td>
<td>300WT</td>
<td>300</td>
<td>400</td>
<td>190</td>
<td>193</td>
<td></td>
</tr>
<tr>
<td>G40.21M</td>
<td>350W</td>
<td>350</td>
<td>450</td>
<td>190</td>
<td>193</td>
<td></td>
</tr>
<tr>
<td>G40.21M</td>
<td>350WT</td>
<td>$r \leq 65$</td>
<td>$65 &lt; r \leq 100$</td>
<td>300</td>
<td>450</td>
<td>192</td>
</tr>
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<td>National Standards</td>
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<td>25H</td>
<td></td>
<td>225</td>
<td>365</td>
<td>137</td>
<td>154</td>
<td></td>
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<td>25C</td>
<td></td>
<td>225</td>
<td>365</td>
<td>137</td>
<td>154</td>
<td></td>
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<tr>
<td>260</td>
<td></td>
<td>225</td>
<td>400</td>
<td>157</td>
<td>171</td>
<td></td>
</tr>
<tr>
<td>26H</td>
<td></td>
<td>225</td>
<td>400</td>
<td>157</td>
<td>171</td>
<td></td>
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<tr>
<td>ISO Specifications</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ISO 880</td>
<td>E270C, D</td>
<td>$r \leq 10$</td>
<td>$10 &lt; r \leq 10$</td>
<td>275</td>
<td>410</td>
<td>104</td>
</tr>
<tr>
<td>ISO 880</td>
<td>E355C, D</td>
<td>$r \leq 10$</td>
<td>$10 &lt; r \leq 40$</td>
<td>275</td>
<td>410</td>
<td>104</td>
</tr>
<tr>
<td>EN Specifications</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EN 10025</td>
<td>S 275, J2</td>
<td>$r \leq 10$</td>
<td>$10 &lt; r \leq 11/2$</td>
<td>365</td>
<td>470</td>
<td>188</td>
</tr>
<tr>
<td>EN 10025</td>
<td>S 275, J2</td>
<td>$r \leq 10$</td>
<td>$10 &lt; r \leq 11/2$</td>
<td>365</td>
<td>470</td>
<td>188</td>
</tr>
<tr>
<td>EN 10025</td>
<td>S 275, J2</td>
<td>$r \leq 10$</td>
<td>$10 &lt; r \leq 11/2$</td>
<td>365</td>
<td>470</td>
<td>188</td>
</tr>
</tbody>
</table>

* By agreement between the Purchaser and the Manufacturer, the tensile strength of ASTM A537M, Class 2, A676M, Grade B, and A641M, Class 2 materials may be increased to 585 MPa minimum and 660 MPa maximum. The tensile strength of the other listed materials may be increased to 560 MPa minimum and 620 MPa maximum. When this is done, the allowable stresses shall be determined as stated in 5.6.2.1 and 5.6.2.2.

* By agreement between the Purchaser and the Manufacturer, the tensile strength of ASTM A537M, Class 2 materials may be increased to 530 MPa minimum and 600 MPa maximum. The tensile strength of the other listed materials may be increased to 500 MPa minimum and 560 MPa maximum. When this is done, the allowable stresses shall be determined as stated in 5.6.2.1 and 5.6.2.2.
Required Calculation

- Thicknesses
- Attachments
- Wind and stability
- Seismic
- Internal pressure
- External pressure
Thickness Calculation

- Bottom and annular plate thickness calculation
- Shell plate thickness calculation
- Roof plate thickness calculation
SHELL DESIGN
- Liquid levels
5.6. SHELL DESIGN

5.6.1.1 The required shell thickness shall be the greater of the design shell thickness, including any corrosion allowance, or the hydrostatic test shell thickness, but the shell thickness shall not be less than the following:

<table>
<thead>
<tr>
<th>Nominal Tank Diameter</th>
<th>Nominal Plate Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m)</td>
<td>(ft)</td>
</tr>
<tr>
<td>&lt; 15</td>
<td>&lt; 50</td>
</tr>
<tr>
<td>15 to &lt; 36</td>
<td>50 to &lt; 120</td>
</tr>
<tr>
<td>36 to 60</td>
<td>120 to 200</td>
</tr>
<tr>
<td>&gt; 60</td>
<td>&gt; 200</td>
</tr>
</tbody>
</table>

**NOTE 1** Unless otherwise specified by the Purchaser, the nominal tank diameter shall be the centerline diameter of the bottom shell-course plates.

**NOTE 2** The thicknesses specified are based on erection requirements.

**NOTE 3** When specified by the Purchaser, plate with a nominal thickness of 6 mm may be substituted for 1/4-in. plate.

**NOTE 4** For diameters less than 15 m (50 ft) but greater than 3.2 m (10.5 ft), the nominal thickness of the lowest shell course shall not be less than 6 mm (1/4 in.).
5.6.1.2 Unless otherwise agreed to by the Purchaser, the shell plates shall have a minimum nominal width of 1800 mm (72 in.)

5.6.1.3 When the allowable stress for an upper shell course is lower than the allowable stress of the next lower shell course, the lower shell course thickness shall be no less than the thickness required of the upper shell course for product and hydrostatic test loads by 5.6.3 or 5.6.4.
DESIGN (SHELL DESIGN)

- Shell Design
  - 1-Foot Method
  - Variable-Design-Point Method
  - Elastic Analysis
  - Annex A

Hossein Sadeghi

WELDED TANKS FOR OIL STORAGE (Rev. 0)
1-Foot Method: The 1-foot method calculates the thicknesses required at design points 0.3 m (1 ft) above the bottom of each shell course.

Variable-Design-Point Method: Design by the variable-design-point method gives shell thicknesses at design points that result in the calculated stresses being relatively close to the actual circumferential shell stresses.

Elastic Analysis: For tanks where L/H is greater than 1000/6, the selection of shell thicknesses shall be based on an elastic analysis.

Annex A: Annex A permits an alternative shell design with a fixed allowable stress of 145 MPa (21,000 lbf/in.2) and a joint efficiency factor of 0.85 or 0.70. This design may only be used for tanks with shell thicknesses less than or equal to 13 mm.
• Hoop (circumferential) stress:

This is the stress trying to split the vessel open along its length. Confusingly, this acts on the longitudinal weld seam (if there is one).
Figure 7.1 Forces and stresses in a pressurized cylinder.
• **circumferential stress**: 

\[ S_C = \frac{RP}{t} \]

where: \( R \) = inside radius of the cylinder  
\( t \) = thickness of cylinder  
\( P \) = internal pressure

• **Longitudinal stress**: 

\[ S_L = \frac{RP}{2t} \]

where: \( R \) = inside radius of the cylinder  
\( t \) = thickness of cylinder  
\( P \) = internal pressure
• Liquid static head stress:

I) \( S_c = \frac{RP}{t} \)

II) \( P = \rho gh \)

Substituting II in I

III) \( S_c = \frac{\rho gh}{t} \)  \( \text{or} \)  \( t = \frac{D \times G \times 9.8 \times H}{S} \)

\( t = 4.9 \frac{D \times G \times H}{S} \)
5.6.3. Calculation of Thickness by the 1-Foot Method

- This method shall not be used for tanks larger than 61 m (200 ft) in diameter.
- The required minimum thickness of shell plates shall be the greater of the values computed by the following formulas:

In SI units:

\[
t_d = \frac{4.9D(H - 0.3)G}{S_d} + CA
\]

\[
t_t = \frac{4.9D(H - 0.3)}{S_t}
\]

\[t = 4.9 \times D \times G \times (H - 0.3) / S\]
Example

- Inside diameter: 34000 mm
- Tank Height: 8000 mm
- Corrosion allowance: 1.5 mm for all plates
- Material: A 283 C
- Service: Water, Density: 1000 Kg/m³
- Design pressure: Atm.
- Design liquid level: 6600 mm
- Plate width: 1500 mm + 500 mm for last course
- Course #1:

\[ t_1 = \text{Max. } (t_d, t_t) \]

\[ T_d = 4.9 \times 34 \text{m} \times (6.6 - 0.3) \times 1 / 137 = 7.66 \text{mm} + 1.5 \text{mm} = 9.16 \text{mm} \]

\[ T_t = 4.9 \times 34 \text{m} \times (6.6 - 0.3) / 154 = 6.82 \text{mm} \]

So, the minimum required thickness of first shell course is \( \text{Max } (9.16, 6.82) = 9.16 \) and the selected thickness for first course is 10 mm.
- Course # 2 :

\[ t_2 = \text{Max.} (t_d, t_t) \]

\[ T_d = 4.9 \times 34 \text{m} \times (6.6 - 1.5 - 0.3) \times 1 / 137 = 5.83 \text{ mm} + 1.5 \text{ mm} = 7.33 \text{ mm} \]

\[ T_t = 4.9 \times 34 \text{ m} \times (6.6 - 1.5 - 0.3) / 154 = 5.19 \text{ mm} \]

So, The minimum required thickness of 2th shell course is \( \text{Max} (7.33, 5.19) = 7.33 \) and the selected thickness for 2th course is 8 mm
### Example

#### Thickness of Shell Plates

<table>
<thead>
<tr>
<th>Course No</th>
<th>course height (mm)</th>
<th>H (mm)</th>
<th>St (Mpa)</th>
<th>Sd (Mpa)</th>
<th>T test (mm)</th>
<th>T design (mm)</th>
<th>Tactual (mm)</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1500</td>
<td>6600</td>
<td>154</td>
<td>137</td>
<td>6.82</td>
<td>9.1612</td>
<td>10</td>
<td>A 283 C or equivalent</td>
</tr>
<tr>
<td>2</td>
<td>1500</td>
<td>5100</td>
<td>154</td>
<td>137</td>
<td>5.19</td>
<td>7.3371</td>
<td>8</td>
<td>A 283 C or equivalent</td>
</tr>
<tr>
<td>3</td>
<td>1500</td>
<td>3600</td>
<td>154</td>
<td>137</td>
<td>3.57</td>
<td>5.5130</td>
<td>6</td>
<td>A 283 C or equivalent</td>
</tr>
<tr>
<td>4</td>
<td>1500</td>
<td>2100</td>
<td>154</td>
<td>137</td>
<td>1.95</td>
<td>3.6889</td>
<td>6</td>
<td>A 283 C or equivalent</td>
</tr>
<tr>
<td>5</td>
<td>1500</td>
<td>600</td>
<td>154</td>
<td>137</td>
<td>0.32</td>
<td>1.8648</td>
<td>6</td>
<td>A 283 C or equivalent</td>
</tr>
<tr>
<td>6</td>
<td>500</td>
<td>-900</td>
<td>154</td>
<td>137</td>
<td>-1.30</td>
<td>1.1566</td>
<td>6</td>
<td>A 283 C or equivalent</td>
</tr>
</tbody>
</table>

\[
t_d = \frac{4.9D(H-0.3)G}{S_d} + CA
\]

\[
t_t = \frac{4.9D(H-0.3)}{S_t}
\]
1) Question!

- Inside diameter: 30000 mm
- Tank Height: 16000 mm
- Corrosion allowance: 3 mm for all plates
- Material:
  ✓ Course 1,2: A 516 70
  ✓ Other courses: A 283 C
- Service: Gasoil, Density: 900 Kg/m³
- Design pressure: Atm.
- Design liquid level: 14200 mm
- Plate width: 2000 mm
- Minimum Amb. Temperature: -15 °C

- Shell and Bottom Plate thickness?
- Impact test?
2) Question!

- Inside diameter: 8000 mm
- Tank Height: 6000 mm
- Corrosion allowance: 3 mm for all plates
- Material: A 283 C
- Service: Oil, Density: 850 Kg/m³
- Design pressure: Atm.
- Design liquid level: 5100 mm
- Plate width: 1800 mm
- Minimum Amb. Temperature: -12 °C

- Shell and Bottom Plate thickness?
- Impact test?
VARIABLE DESIGN POINT

1. First method:

\[ L = \sqrt{500D} \]

2. Hydrotest and design conditions:

\[ t_{pl} = \frac{4.9D(H-0.3)}{S_d} + CA \]

\[ t_{el} = \frac{4.9D(H-0.3)}{S_t} \]

3. Calculations:

\[ t_{ld} = (1.06 - \frac{0.0696D}{H}) \left( \frac{H_G}{S_d} \right) \left( \frac{4.9HDG}{S_d} \right) + CA \]

\[ t_{lt} = (1.06 - \frac{0.696D}{H}) \left( \frac{H}{S_t} \right) \left( \frac{4.9HD}{S_t} \right) \]

For design condition, \( t_{ld} \) need not be greater than \( t_{pl} \).
For test condition, \( t_{lt} \) need not be greater than \( t_{pl} \).

4. Additional notes:

\[ \frac{H}{S_{pl}} = h_{pl} \]
تیم و تُرسیم‌سازی برای ترکیبی از این الگوریتم‌ها، قرار است این تیم نتایج را داشته باشد.

\[ t_2 = t_1 \quad \Rightarrow \quad 1.375 \quad \text{RATIO} \]

\[ t_2 = t_{2a} \quad \Rightarrow \quad 2.625 \quad \text{RATIO} \]

\[ t_2 = t_{2a} + (t_1 - t_{2a}) \left[ 2.1 - \frac{n_1}{1.25(t_1)^{0.5}} \right] \quad \Rightarrow \quad 1.375 \quad \text{RATIO} < 2.625 \]

\[ 5.6.4 \quad 5.6.4.6 \quad \text{تشخیص: } t_{2a} \]

\[ (r_t u)^{0.5} \]

\[ x_1 = 0.61 (r_t u)^{0.5} + 320 \quad \text{CH} \]

\[ x_2 = 1000 \quad \text{CH} \]

\[ x_3 = 1.22 (r_t u)^{0.5} \]

\[ c = \frac{K_0^5 (k+1)}{1+K_1^5} \]

\[ k = \frac{t_L}{t_u} \]

\[ t_L = \text{CORRODED THICKNESS OF THE LOWER SHELL COURSE} \]

\[ H = \text{DESIGN LIQUID LEVEL} \]

\[ t_{Lx} = \text{MAX.} \quad \left\{ \begin{array}{c} t_{dn} = \frac{4.9 D (H - x_{1000})}{S_d} + C_{A} \\ t_{nu} = \frac{4.9 D (H - x_{1000})}{S_t} \end{array} \right. \]

کد Converge \( t_x \) را استفاده کنید.
BOTTOM AND ANNULAR PLATE
5.4. Bottom Plates

5.4.1 All bottom plates shall have a corroded thickness of not less than 6 mm.

All rectangular and sketch plates shall have a nominal width of not less than 1800 mm.

5.4.2 Bottom plates of sufficient size shall be ordered so that, when trimmed, at least a 50 mm (2 in.) width will project outside the shell or meet requirements given in 5.1.5.7 d whichever is greater.

5.4.4 Unless otherwise specified on the Data Sheet, Line 12, tank bottoms requiring sloping shall have a minimum slope of 1:120 upwards toward center of the tank.
5.5. ANNULAR BOTTOM PLATES

5.5.1. When the bottom shell course is designed using the allowable stress for materials in Group IV, IVA, V, or VI, butt-welded annular bottom plates shall be used (see 5.1.5.6). When the bottom shell course is of a material in Group IV, IVA, V, or VI and the maximum product stress (see 5.6.2.1) for the first shell course is less than or equal to 160 MPa (23,200 lbf/in.2) or the maximum hydrostatic test stress (see 5.6.2.2) for the first shell course is less than or equal to 171 MPa (24,900 lbf/in.2), lap-welded bottom plates (see 5.1.5.4) may be used in lieu of butt-welded annular bottom plates.

5.1.5.6 Bottom annular-plate radial joints shall be butt-welded in accordance with 5.1.5.5 and shall have complete penetration and complete fusion. The backing strip, if used, shall be compatible for welding the annular plates together.
• **5.5.4** The ring of annular plates shall have a circular outside circumference, but may have a regular polygonal shape inside the tank shell, with the number of sides equal to the number of annular plates. These pieces shall be welded in accordance with 5.1.5.6 and 5.1.5.7, Item b.

• **5.5.5** In lieu of annular plates, the entire bottom may be butt-welded provided that the requirements for annular plate thickness, welding, materials, and inspection are met for the annular distance specified in 5.5.2.

• **5.5.3.** The thickness of the annular bottom plates shall not be less than the greater thickness determined using Table 5.1a and Table 5.1b for product design (plus any specified corrosion allowance) or for hydrostatic test design. Table 5.1a and Table 5.1b are applicable for effective product height of $H \times G \leq 23$ m (75 ft). Beyond this height an elastic analysis must be made to determine the annular plate thickness.
Table 5.1a—Annular Bottom-Plate Thicknesses ($t_b$) (SI)

<table>
<thead>
<tr>
<th>Plate Thickness$^a$ of First Shell Course (mm)</th>
<th>Stress$^b$ in First Shell Course (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>≤ 190</td>
</tr>
<tr>
<td>$t \leq 19$</td>
<td>6</td>
</tr>
<tr>
<td>$19 &lt; t \leq 25$</td>
<td>6</td>
</tr>
<tr>
<td>$25 &lt; t \leq 32$</td>
<td>6</td>
</tr>
<tr>
<td>$32 &lt; t \leq 40$</td>
<td>8</td>
</tr>
<tr>
<td>$40 &lt; t \leq 45$</td>
<td>9</td>
</tr>
</tbody>
</table>

$^a$ Plate thickness refers to the corroded shell plate thickness for product design and nominal thickness for hydrostatic test design.

$^b$ The stress to be used is the maximum stress in the first shell course (greater of product or hydrostatic test stress). The stress may be determined using the required thickness divided by the thickness from “a” then multiplied by the applicable allowable stress:

Product Stress = $\left( \frac{(t_d - CA)}{corroded \ t} \right) \times (S_d)$

Hydrostatic Test Stress = $\left( \frac{t_t}{nominal \ t} \right) \times (S_t)$

NOTE: The thicknesses specified in the table, as well as the width specified in 5.5.2, are based on the foundation providing uniform support under the full width of the annular plate. Unless the foundation is properly compacted, particularly at the inside of a concrete ringwall, settlement will produce additional stresses in the annular plate.
• 5.5.2. Annular bottom plates shall have a radial width that provides at least 600 mm (24 in.) between the inside of the shell and any lap-welded joint in the remainder of the bottom. Annular bottom plate projection outside the shell shall meet the requirements of 5.4.2. A greater radial width of annular plate is required when calculated as follows:

• Minimum Width of Annular plate:

\[
\text{overlap length (min. } 5 \times t_b) + t_{shell} + 50 \text{ mm } + \text{max. } (L ; 600)
\]
\[ L = 2 \, t_b \sqrt[2]{\frac{F_y}{2 \gamma G H}} \]

where

- \( L \) is the minimum width of annular plate as measured from inside edge of the shell to the edge of the plate in the remainder of the bottom, mm (inch);
- \( F_y \) is the minimum yield strength of the annular plate at ambient temperature, MPa (psi);
- \( t_b \) is the nominal thickness of the annular plate (see 5.5.3), mm (in.);
- \( H \) is the maximum design liquid level (see 5.6.3.2), m (ft);
- \( G \) is the design specific gravity of the liquid to be stored, as specified by the Purchaser, not greater than 1.0;
- \( \gamma \) is the density factor of water. MPa per meter, (psi per foot) SI: 9.81/1000, USC: 62.4/144.
5.9.6 TOP WIND GIRDER

5.9.6.1. The required minimum section modulus of the stiffening ring shall be determined by the following equation:

\[ Z = \frac{D^2 H_2}{17} \left( \frac{V}{190} \right)^2 \]

- **Z** is the required minimum section modulus, in cm³;
- **D** is the nominal tank diameter (for tanks in excess of 61 m diameter, the diameter shall be considered to be 61 m when determining the section modulus), in meters (m);
- **H₂** is the height of the tank shell, in meters, including any freeboard provided above the maximum filling height as a guide for a floating roof;
- **V** is the design wind speed (3-sec gust), in km/h (see 5.2.1[k]).
5.9.6.2 For tanks larger than 61 m (200 ft) in diameter, an additional check for
the minimum required moment of inertia for the top-stiffening ring shall be
performed. The required minimum moment of inertia of the stiffening ring shall
be determined by the following equations:

\[ I = 3583 \times H_2 \times D^3 \times (V/190)^2 / E \]

- \( I \) is the required minimum moment of inertia (cm\(^4\));
- \( D \) is the nominal diameter of the tank, in meters (m);
- \( H_2 \) is the height of the tank shell (m), including any freeboard provided above the maximum
  filling height as a guide for a floating roof;
- \( E \) is the modulus of elasticity (MPa) at maximum design temperature;
- \( V \) is the design wind speed (3-sec gust) (km/h) (see 5.2.1[k]).
Intermediate Wind Girder

- Sturm-Liouville Equations (Singular Sturm-Liouville problems)

\[ T \text{ (uniform)} \]

In most practical situations an eigenvalue is associated with an important physical characteristic of the problem, such as the frequency of vibration of a string or of a metal plate. In such cases the eigenfunction can be considered to describe a “snapshot” of a particular mode of vibration of the string or plate when it vibrates at the frequency determined by the associated eigenvalue. This application, and others that lead to Sturm–Liouville problems, will be developed in detail when partial differential equations are discussed in the context of separation of variables.

Ref. : Advanced engineering mathematics by Alan Jeffrey (University of Newcastle-upon-Tyne)
Intermediate Wind Girder

- Cylinder of pressure vessel

See TABLE 8.1 Shear, moment, slope, and deflection formulas for elastic straight beams
If $\sum W_{tr} > H_1$, wind girder is required.
The maximum height of the unstiffened shell shall be calculated as follows:

\[ H_1 = 9.47t \sqrt{\left(\frac{t}{D}\right)^3 \left(\frac{190}{V}\right)^2} \]

- \( H_1 \) is the maximum height of the unstiffened shell, in meters;
- \( t \) is the nominal thickness, unless otherwise specified, of the thinnest shell course, in millimeters (see Note 1);
- \( D \) is the nominal tank diameter, in meters;
Intermediate Wind Girder

• Transposed width of each shell course having the top shell thickness:

\[ W_{tr} = W \sqrt{\left( \frac{t_{\text{uniform}}}{t_{\text{actual}}} \right)^5} \]

• \( W_{tr} \) is the transposed width of each shell course, in millimeters (inches);
• \( W \) is the actual width of each shell course, in millimeters (inches); \( t_{\text{uniform}} \) is the nominal thickness, unless otherwise specified, of the thinnest shell course, in millimeters (inches);
• \( t_{\text{actual}} \) is the nominal thickness, unless otherwise specified, of the shell course for which the transposed width is being calculated, in millimeters (inches).
Example

- Inside diameter: 34000 mm
- Tank Height: 8000 mm
- Corrosion allowance: 1.5 mm for all plates
- Material: A 283 C
- Service: Water, Density: 1000 Kg/m3
- Design pressure: Atm.
- Design liquid level: 6600 mm
- Plate width: 1500 mm + 500 mm for last course
- Minimum Amb. Temperature: -15 °C

- Anuular plate width and thickness?
- Wind girder calculation?
1) Question!

- Inside diameter: 30000 mm
- Tank Height: 16000 mm
- Corrosion allowance: 3 mm for all plates
- Material:
  - Course 1,2: A 516 70
  - Other courses: A 283 C
- Service: Gasoil, Density: 900 Kg/m3
- Design pressure: Atm.
- Design liquid level: 14200 mm
- Plate width: 2000 mm
- Minimum Amb. Temperature: -15 °C

- Anuular plate width and thickness?
- Wind girder calculation?
Inside diameter: 8000 mm
Tank Height: 6000 mm
Corrosion allowance: 3 mm for all plates
Material: A 283 C
Service: Oil, Density: 850 Kg/m³
Design pressure: Atm.
Design liquid level: 5100 mm
Plate width: 1800 mm
Minimum Amb. Temperature: -12 °C

- Anuular plate width and thickness?
- Wind girder calculation?
Intermediate Wind Girder

- Transposed width of each shell course having the top shell thickness:

\[ W_{tr} = W \sqrt{\left( \frac{t_{\text{uniform}}}{t_{\text{actual}}} \right)^5} \]

- \( W_{tr} \) is the transposed width of each shell course, in millimeters (inches);
- \( W \) is the actual width of each shell course, in millimeters (inches); \( t_{\text{uniform}} \) is the nominal thickness, unless otherwise specified, of the thinnest shell course, in millimeters (inches);
- \( t_{\text{actual}} \) is the nominal thickness, unless otherwise specified, of the shell course for which the transposed width is being calculated, in millimeters (inches).
5.9.7.3 If the height of the transformed shell is greater than the maximum height \( H_1 \), an intermediate wind girder is required.

5.9.7.3.1 For equal stability above and below the intermediate wind girder, the girder should be located at the midheight of the transformed shell. The location of the girder on the actual shell should be at the same course and same relative position as the location of the girder on the transformed shell, using the thickness relationship in 5.9.7.2.
5.9.7.3.2 Other locations for the girder may be used, provided the height of unstiffened shell on the transformed shell does not exceed $H_1$ (see 5.9.7.5).

5.9.7.4 If half the height of the transformed shell exceeds the maximum height $H_1$, a second intermediate girder shall be used to reduce the height of unstiffened shell to a height less than the maximum.

5.9.7.5 Intermediate wind girders shall not be attached to the shell within 150 mm (6 in.) of a horizontal joint of the shell. When the preliminary location of a girder is within 150 mm (6 in.) of a horizontal joint, the girder shall preferably be located 150 mm (6 in.) below the joint; however, the maximum unstiffened shell height shall not be exceeded.
5.9.7.6 The required minimum section modulus of an intermediate wind girder shall be determined by the following equation:

In SI units:

\[ Z = \frac{D^2 h_1}{17} \left( \frac{V}{190} \right)^2 \]

where

- \( Z \) is the required minimum section modulus, in cm\(^3\);
- \( D \) is the nominal tank diameter, in meters;
- \( h_1 \) is the vertical distance, in meters, between the intermediate wind girder and the top angle of the shell or the top wind girder of an open-top tank;
- \( V \) is the design wind speed (3-sec gust), in km/h (see 5.2.1[k]).
Note: The section moduli given in Tables 5.20a and 5.20b for Details c and d are based on the longer leg being located horizontally (perpendicular to the shell) when angles with uneven legs are used.
<table>
<thead>
<tr>
<th>Member Size</th>
<th>Column 1</th>
<th>Column 2</th>
<th>Column 3</th>
<th>Column 4</th>
<th>Column 5</th>
<th>Column 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top Angle: Figure 5.24, Detail a</td>
<td>65 x 65 x 6</td>
<td>6.88</td>
<td>6.77</td>
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<td>—</td>
</tr>
<tr>
<td>65 x 65 x 8</td>
<td>8.46</td>
<td>8.63</td>
<td>—</td>
<td>—</td>
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<td>—</td>
</tr>
<tr>
<td>75 x 75 x 10</td>
<td>13.82</td>
<td>13.97</td>
<td>—</td>
<td>—</td>
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<td>—</td>
</tr>
<tr>
<td>Curb Angle: Figure 5.24, Detail b</td>
<td>65 x 65 x 6</td>
<td>21.03</td>
<td>26.16</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>65 x 65 x 8</td>
<td>33.05</td>
<td>34.67</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>75 x 75 x 8</td>
<td>35.98</td>
<td>37.49</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>75 x 75 x 10</td>
<td>47.24</td>
<td>53.64</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>100 x 100 x 7</td>
<td>83.30</td>
<td>74.88</td>
<td>—</td>
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</tr>
<tr>
<td>100 x 100 x 10</td>
<td>71.09</td>
<td>87.60</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>One Angle: Figure 5.24, Detail c (See Note)</td>
<td>65 x 65 x 6</td>
<td>26.08</td>
<td>25.76</td>
<td>30.73</td>
<td>32.94</td>
<td>34.89</td>
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<tr>
<td>65 x 65 x 8</td>
<td>34.35</td>
<td>36.21</td>
<td>35.51</td>
<td>40.24</td>
<td>41.17</td>
<td>41.77</td>
</tr>
<tr>
<td>100 x 75 x 7</td>
<td>60.54</td>
<td>65.21</td>
<td>60.88</td>
<td>69.48</td>
<td>70.59</td>
<td>70.94</td>
</tr>
<tr>
<td>125 x 75 x 8</td>
<td>69.17</td>
<td>70.08</td>
<td>74.49</td>
<td>77.81</td>
<td>78.34</td>
<td>78.34</td>
</tr>
<tr>
<td>125 x 75 x 10</td>
<td>105.20</td>
<td>110.71</td>
<td>118.91</td>
<td>124.03</td>
<td>126.97</td>
<td>127.78</td>
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<tr>
<td>150 x 75 x 10</td>
<td>134.14</td>
<td>141.38</td>
<td>152.29</td>
<td>154.79</td>
<td>162.76</td>
<td>162.76</td>
</tr>
<tr>
<td>150 x 100 x 10</td>
<td>155.91</td>
<td>171.17</td>
<td>164.11</td>
<td>163.08</td>
<td>166.62</td>
<td>166.62</td>
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<tr>
<td>Two Angles: Figure 5.24, Detail d (See Note)</td>
<td>100 x 75 x 8</td>
<td>181.22</td>
<td>188.49</td>
<td>186.15</td>
<td>201.83</td>
<td>204.02</td>
</tr>
<tr>
<td>100 x 75 x 10</td>
<td>218.81</td>
<td>223.31</td>
<td>229.95</td>
<td>243.41</td>
<td>247.16</td>
<td>249.76</td>
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<td>125 x 75 x 8</td>
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<td>256.94</td>
<td>269.59</td>
<td>274.39</td>
<td>283.46</td>
<td>283.46</td>
</tr>
<tr>
<td>125 x 75 x 10</td>
<td>296.71</td>
<td>308.17</td>
<td>324.94</td>
<td>337.32</td>
<td>342.77</td>
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<tr>
<td>150 x 75 x 8</td>
<td>329.47</td>
<td>355.45</td>
<td>353.12</td>
<td>366.02</td>
<td>372.46</td>
<td>372.46</td>
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<tr>
<td>150 x 75 x 10</td>
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<td>402.92</td>
<td>425.14</td>
<td>443.06</td>
<td>450.91</td>
<td>450.91</td>
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<tr>
<td>150 x 100 x 10</td>
<td>461.11</td>
<td>473.57</td>
<td>465.82</td>
<td>513.69</td>
<td>521.41</td>
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<tr>
<td>Formed Plate: Figure 5.24, Detail e</td>
<td>0 x 250</td>
<td>—</td>
<td>341</td>
<td>375</td>
<td>392</td>
<td>408</td>
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<tr>
<td>0 x 300</td>
<td>—</td>
<td>427</td>
<td>473</td>
<td>486</td>
<td>505</td>
<td>505</td>
</tr>
<tr>
<td>0 x 350</td>
<td>—</td>
<td>519</td>
<td>577</td>
<td>606</td>
<td>618</td>
<td>618</td>
</tr>
<tr>
<td>0 x 400</td>
<td>—</td>
<td>615</td>
<td>687</td>
<td>723</td>
<td>747</td>
<td>747</td>
</tr>
<tr>
<td>0 x 450</td>
<td>—</td>
<td>717</td>
<td>802</td>
<td>848</td>
<td>866</td>
<td>866</td>
</tr>
<tr>
<td>0 x 500</td>
<td>—</td>
<td>824</td>
<td>925</td>
<td>975</td>
<td>998</td>
<td>998</td>
</tr>
<tr>
<td>0 x 550</td>
<td>—</td>
<td>937</td>
<td>1049</td>
<td>1111</td>
<td>1125</td>
<td>1125</td>
</tr>
<tr>
<td>0 x 600</td>
<td>—</td>
<td>1064</td>
<td>1181</td>
<td>1252</td>
<td>1280</td>
<td>1280</td>
</tr>
<tr>
<td>0 x 650</td>
<td>—</td>
<td>1176</td>
<td>1317</td>
<td>1369</td>
<td>1432</td>
<td>1432</td>
</tr>
<tr>
<td>0 x 700</td>
<td>—</td>
<td>1304</td>
<td>1459</td>
<td>1551</td>
<td>1589</td>
<td>1589</td>
</tr>
<tr>
<td>0 x 750</td>
<td>—</td>
<td>1436</td>
<td>1687</td>
<td>1709</td>
<td>1752</td>
<td>1752</td>
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<tr>
<td>0 x 800</td>
<td>—</td>
<td>1573</td>
<td>1759</td>
<td>1873</td>
<td>1921</td>
<td>1921</td>
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<tr>
<td>0 x 850</td>
<td>—</td>
<td>1710</td>
<td>1917</td>
<td>2043</td>
<td>2098</td>
<td>2098</td>
</tr>
<tr>
<td>0 x 900</td>
<td>—</td>
<td>1848</td>
<td>2064</td>
<td>2228</td>
<td>2295</td>
<td>2295</td>
</tr>
<tr>
<td>0 x 950</td>
<td>—</td>
<td>2016</td>
<td>2248</td>
<td>2368</td>
<td>2483</td>
<td>2483</td>
</tr>
<tr>
<td>0 x 1000</td>
<td>—</td>
<td>2174</td>
<td>2421</td>
<td>2584</td>
<td>2654</td>
<td>2654</td>
</tr>
</tbody>
</table>

**NOTE:** The section moduli for Details c and d are based on the longer leg being located horizontally (perpendicular to the shell) when angles with uneven legs are used.
5.9.7.6.2 The section modulus of the intermediate wind girder shall be based on the properties of the attached members and may include a portion of the tank shell for a distance above and below the attachment to the shell, in mm (in.)

\[ 13.4 (Dt)^{0.5} \]

where

- \( D \) is the nominal tank diameter, in meters;
- \( t \) is the nominal shell thickness, unless otherwise specified, at the attachment, in millimeters.
**INTERMEDIATE WIND GIRDER**

**WIND GIRDER CALCULATION**
(calculated in corroded condition)

\[ V = 162 \text{ Km/hr} \]
\[ t = 6 - 1.5 = 4.5 \]

\[ H_1 = 9.47t \sqrt[3]{\frac{t}{D}} \left( \frac{190}{V} \right)^2 \]

\[ H_1 = 2822.54 \text{ m} \]

\[ W_{tr} = W^2(t \text{ uniform} / t \text{ actual})^{2.5} \]

<table>
<thead>
<tr>
<th>Course No</th>
<th>course height(mm)</th>
<th>Actual Thickness</th>
<th>Uniform Thickness</th>
<th>Wtr</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1500</td>
<td>10</td>
<td>4.5</td>
<td>305.90</td>
</tr>
<tr>
<td>2</td>
<td>1500</td>
<td>8</td>
<td>4.5</td>
<td>598.19</td>
</tr>
<tr>
<td>3</td>
<td>1500</td>
<td>6</td>
<td>4.5</td>
<td>1500.00</td>
</tr>
<tr>
<td>4</td>
<td>1500</td>
<td>6</td>
<td>4.5</td>
<td>1500.00</td>
</tr>
<tr>
<td>5</td>
<td>1500</td>
<td>6</td>
<td>4.5</td>
<td>1500.00</td>
</tr>
<tr>
<td>6</td>
<td>500</td>
<td>6</td>
<td>4.5</td>
<td>500.00</td>
</tr>
</tbody>
</table>

\[ \sum W_{tr} = 5904.09 \text{ mm} \]
INTERMEDIATE WIND GIRDER

$$\Sigma W_{tr} \div H_1 = 2.0918$$

The max. height of the unstiff. shell is less than tank height. So, two intermediate Wind Girder is required at +4800 and +7000 elevations.

The required minimum section modulus of intermediate wind girders shall be determined by the following equation:

$$Z = \frac{D^2 H_1}{17} \left( \frac{V}{190} \right)^2 = 139.53 \text{ cm}^3$$

Selected angle size for wind girder as per detail "C" of Figure 5-20 is: L150x75x10

Note: The section moduli for Detail C are based on the longer leg being located horizontally (perpendicular to the shell).
ROOF
5.10 ROOFS

- Internal Floating roof
- External Floating roof
- A supported cone roof
- A Supported Dome roof
- A self-supporting cone roof
- A self-supporting dome roof
- A self-supporting umbrella roof
- Frangible roof
5.10.2.2. Roof plates shall have a nominal thickness of not less than 5 mm (3/16 in.) or 7-gauge sheet. Increased thickness may be required for supported cone roofs (see 5.10.4.4). Any required corrosion allowance for the plates of self-supporting roofs shall be added to the calculated thickness unless otherwise specified by the Purchaser. Any corrosion allowance for the plates of supported roofs shall be added to the greater of the calculated thickness or the minimum thickness or [5 mm (3/16 in.) or 7-gauge sheet].
• **5.10.4 Supported Cone Roofs**

The slope of the roof shall be 1:16 (3.6°) or greater if specified by the Purchaser.

• **5.10.5 Self-Supporting Cone Roofs**

Self-supporting cone roofs shall conform to the following requirements:

\[ \theta \leq 37 \text{ degrees (slope = 9:12)} \]

\[ \theta \geq 9.5 \text{ degrees (slope = 2:12)} \]
5.10.5 Self-Supporting Cone Roofs

Nominal thickness shall not be less than the greatest of:

\[
\frac{D}{4.8 \sin \theta \sqrt{\frac{B}{2.2}}} + CA, \text{ or } \frac{D}{5.5 \sin \theta \sqrt{\frac{U}{2.2}}} + CA, \text{ or } 5 \text{ mm}
\]

where

- \( D \) is the nominal diameter of the tank shell, in feet;
- \( B \) is the greater of load combinations 5.2.2 (e)(1) and (e)(2) with balanced snow load \( S_b \) (lbf/ft^2);
- \( U \) is the greater of load combinations 5.2.2 (e)(1) and (e)(2) with unbalanced snow load \( S_u \) (lbf/ft^2);
- \( \theta \) is the angle of cone elements to the horizontal, in degrees;
- \( CA \) is the corrosion allowance.

Note: Corroded thickness shall not be more than 13 mm.
5.2.2 Load Combinations

e) Gravity Loads:

1) $D_L + (L_r \text{ or } S_u \text{ or } S_b) + F_{pe} P_e$

2) $D_L + P_e + 0.4(L_r \text{ or } S_u \text{ or } S_b)$

- The external pressure combination factor ($F_{pe}$) is defined as the ratio of normal operating external pressure to design external pressure, with a minimum value of 0.4.
• **5.10.6 Self-Supporting dome and umbrella Roofs**

Nominal thickness shall not be less than the greatest of:

\[
\frac{r_r}{2.4}\sqrt{\frac{B}{2.2}} + \text{CA}, \text{ or } \frac{r_r}{2.7}\sqrt{\frac{U}{2.2}} + \text{CA}, \text{ or } 5 \text{ mm}
\]

Minimum radius = 0.8\(D\) (unless otherwise specified by the Purchaser)

Maximum radius = 1.2\(D\)

where

- \(D\) is the nominal diameter of the tank shell, in meters;
- \(B\) is the greater of load combinations 5.2.2 (e)(1) and (e)(2) with balanced snow load \(S_b\) (kPa);
- \(U\) is the greater of load combinations 5.2.2 (e)(1) and (e)(2) with unbalanced snow load \(S_u\) (kPa);
- \(r_r\) is the roof radius, in meters.

Note: *Corroded thickness shall not be more than 13 mm.*
• **5.1.5.9 Roof and Top-Angle Joints**

a) Roof plates shall, as a minimum, be welded on the top side with a continuous full-fillet weld on all seams. Buttwelds are also permitted.

b) For frangible roofs, roof plates shall be attached to the top angle of a tank with a continuous fillet weld on the top side only, as specified in 5.10.2.6. For non-frangible roofs, alternate details are permitted.

c) The top-angle sections, tension rings, and compression rings shall be joined by butt-welds having complete penetration and fusion. Joint efficiency factors need not be applied when conforming to the requirements of 5.10.5 and 5.10.6.

d) At the option of the Manufacturer, for self-supporting roofs of the cone, dome, or umbrella type, the edges of the roof plates may be flanged horizontally to rest flat against the top angle to improve welding conditions.
• e) Except as specified for open-top tanks in 5.9, for tanks with frangible joints per 5.10.2.6, for self-supporting roofs in 5.10.5, and 5.10.6, and for tanks with the flanged roof-to-shell detail described in Item f below, tank shells shall be supplied with top angles of not less than the following sizes:

<table>
<thead>
<tr>
<th>Tank Diameter ((D))</th>
<th>Minimum Top Angle Size(^a) (mm)</th>
<th>Minimum Top Angle Size(^a) (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(D \leq 11\ m, (D \leq 35\ ft))</td>
<td>50 × 50 × 5</td>
<td>2 × 2 × 3/16</td>
</tr>
<tr>
<td>11\ m &lt; (D \leq 18\ m, (35\ ft &lt; D \leq 60\ ft))</td>
<td>50 × 50 × 6</td>
<td>2 × 2 × 1/4</td>
</tr>
<tr>
<td>(D &gt; 18\ m, (D &gt; 60\ ft))</td>
<td>75 × 75 × 10</td>
<td>3 × 3 × 3/8</td>
</tr>
</tbody>
</table>

• Roof-to-shell connection details per Figure F.2 are permissible provided that the design effective area (crosshatched section) is greater than or equal to the design effective area provided by the minimum top angle size listed above.
**Figure F.2—Permissible Details of Compression Rings**

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

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

**NOTE 3** The unstiffened length of the angle or bar, L, shall be limited to $2600(F_y)^{1/2}$ mm [3000(F_y)^{1/2} in] where $F_y$ is the minimum specified yield strength, MPa (ksi) and $t = t_b$ or $t_b$, as applicable.

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

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

- $w_n = \text{maximum width of participating roof}$
  
  $w_n = 0.3(R_b t_b)^{1/2}$ or 200 mm (12 in.) whichever is less.

- $R_o = \text{inside radius of tank shell}$

- $R_n = \text{length of the normal to the roof, measured from the}$
  
  vertical centerline of the tank $= R_o / (\sin \theta)$

- $\theta = \text{angle between roof and horizontal}$
5.10.2.2. The participating area at the roof-to-shell joint shall be determined using Figure F.2 and the nominal material thickness less any corrosion allowance shall equal or exceed the following:

\[
\frac{pD^2}{8F_a \tan \theta}
\]

where

- \(p\) is the greater of load combinations 5.2.2 (e)(1) and (e)(2);
- \(D\) is the nominal diameter of the tank shell;
- \(\theta\) is the angle of cone elements to the horizontal;
- \(F_a\) equals \((0.6 \ F_y)\), the least allowable tensile stress for the materials in the roof-to-shell joint;
- \(F_y\) is the Least Yield Strength of roof-to-shell joint material at maximum design temperature.
A shell + A roof + A angle > A required
Top Angle

- $A_{shell} = W_c \times t_s$

- $W_c = \text{maximum width of participating shell} = 0.6 (R_c t)^{0.5}$

- $A_{shell} = W_h \times t_h$

- $W_h = \text{maximum width of participating roof} = \text{Min.} (0.3 (R_2 t_h)^{0.5} ; 300)$

Where:

- $R_c = \text{inside radius of tank shell}$
- $R_2 = \text{length of the normal to the roof, measured from the vertical centerline of the tank} = \frac{R_c}{\sin \theta}$
OPENINGS
Openings

**KEY**

- **RTR** - Regular-Type Reinforced Opening (nozzle or manhole) with diamond or circular shape reinforcing plate or insert plate that does not extend to the bottom (see Figure 5.7a and Figure 5.8).

- **LTR** - Low-Type Reinforced Opening (nozzle or manhole) using tombstone type reinforcing plate or insert plate that extends to the bottom (see Figure 5.8, Detail (a) and Detail (b)).

- **S-N** - Shell openings with neither a reinforcing plate nor with a thickened insert plate (i.e. integrally reinforced shell openings; or openings not requiring reinforcing).
<table>
<thead>
<tr>
<th>Variables</th>
<th>Reference</th>
<th>Minimum Dimension Between Weld Toes or Weld Centerline (Notes 1 and 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shell $t$</td>
<td>Condition</td>
<td>A (2)</td>
</tr>
<tr>
<td>$t \leq 12.5$ mm</td>
<td>As welded</td>
<td>5.7.3.2</td>
</tr>
<tr>
<td>(t $\leq \frac{1}{2}$ in.)</td>
<td>or PWHT</td>
<td>5.7.3.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.7.3.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.7.3.4</td>
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</tbody>
</table>

$> 12.5$ mm ($t > \frac{1}{2}$ in.) As Welded 5.7.3.1.a 8$W$ or 250 mm (10 in.) 8$W$ or 250 mm (10 in.) 8$W$ or 250 mm (10 in.) 8$W$ or 150 mm (6 in.) 8$r$ or $\frac{1}{2}r$ 8$r$

PWHT 5.7.3.2 150 mm (6 in.) 75 mm (3 in.) or $2\frac{1}{2}t$ 75 mm (3 in.) or $2\frac{1}{2}t$ 75 mm (3 in.) or $2\frac{1}{2}t$ 75 mm (3 in.) or $2\frac{1}{2}t$

Table 5.6a and Table 5.6b 8$r$ or $\frac{1}{2}r$ 8$r$

**NOTE 1** If two requirements are given, the minimum spacing is the greater value, except for dimension "F." See Note 4.

**NOTE 2** $t$ = shell thickness. 8$W$ = 8 times the largest weld size for reinforcing plate or insert plate periphery weld (fillet or butt-weld) from the toe of the periphery weld to the centerline of the shell butt-weld.

**NOTE 3** $D$ = spacing distance established by minimum elevation for low-type reinforced openings from Table 5.6a and Table 5.6b, column 9.

**NOTE 4** Purchaser option to allow shell openings to be located in horizontal or vertical shell butt-welds. See Figure 5.9.

$r$ = shell thickness, $r$ = radius of opening. Minimum spacing for dimension $F$ is the lesser of $8r$ or $\frac{1}{2}r$.

Figure 5.6—Minimum Weld Requirements for Openings in Shells According to 5.7.3
Top Angle

Shell horizontal butt-weld

Shell vertical butt-weld

Bottom plates or annular plates

KEY

14  RTR  =  Regular-Type Reinforced Opening (nozzle or manhole) with diamond or circular shape reinforcing plate, or insert plate, or thickened insert plate, that does not extend to the bottom (see Figure 5.7A and Figure 5.8).

14  LTR  =  Low-Type Reinforced Opening (nozzle or manhole) using tombstone type reinforcing plate, insert plate, or thickened insert plate that extends to the bottom [see Figure 5.8, Detail (a) and Detail (b)].

14  S-N  =  Shell openings with neither a reinforcing plate nor with a thickened insert plate (i.e. integrally reinforced shell openings; or openings not requiring reinforcing).
<table>
<thead>
<tr>
<th>Shell t</th>
<th>Condition</th>
<th>Minimum Dimension Between Weld Toes or Weld Centerline (Notes 1, 2, 3, and 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 13 mm (t ≤ 1/2 in.)</td>
<td>As welded or PWHT</td>
<td>A: 150 mm (6 in.) B: 75 mm (3 in.) C: 75 mm (3 in.) D (5 only): Table 5.6a and Table 5.6b E: 75 mm (3 in.) F (6): Lesser of 8t or 1/2 r G (6): 8t</td>
</tr>
<tr>
<td>&gt; 13 mm (t &gt; 1/2 in.)</td>
<td>As welded</td>
<td>A: 8W or 250 mm (10 in.) B: 8W or 250 mm (10 in.) C: 8W or 250 mm (10 in.) or 21/2 ( t ) D (5 only): Table 5.6a and Table 5.6b E: 8W or 150 mm (6 in.) F (6): Lesser of 8t or 1/2 r G (6): 8t</td>
</tr>
<tr>
<td>&gt; 13 mm (t &gt; 1/2 in.)</td>
<td>PWHT</td>
<td>A: 150 mm (6 in.) B: 75 mm (3 in.) or 21/2 ( t ) C: 75 mm (3 in.) or 21/2 ( t ) or 21/2 ( t ) or 21/2 ( t ) D (5 only): Table 5.6a and Table 5.6b E: 75 mm (3 in.) or 21/2 ( t ) or 21/2 ( t ) or 21/2 ( t ) or 21/2 ( t ) F (6): Lesser of 8t or 1/2 r G (6): 8t</td>
</tr>
</tbody>
</table>

**NOTE 1** If two requirements are given, the minimum spacing is the greater value, unless otherwise noted.

**NOTE 2** Weld spacings are measured to the toe of a fillet-weld, the centerline of an insert or thickened insert plate butt-weld, or the centerline of a shell butt-weld.

**NOTE 3** \( t \) = shell nominal thickness.

**NOTE 4** \( W \) = the largest weld size around the periphery of the fitting(s): for fillet welds the leg length along the tank shell, for butt welds the thickness of the insert plate at the weld joint.

**NOTE 5** \( D \) = spacing distance established by minimum elevation for low-type reinforced openings from Table 5.6a and Table 5.6b, column 9.

**NOTE 6** Purchaser option to allow shell openings to be located in horizontal or vertical shell butt-welds. See Figure 5.9.
Tables and Figures

- **Shell Manholes:**
  - Cover Plate and Bolting Flange of shell manhole: Table 5-3
  - Dimension of shell manhole neck thickness: Table 5.4
  - Dimension of Bolt circle diameter and cover plate diameter of shell manhole: Table 5.5
  - Standard figure of shell manhole: Figure 5.7
- **Shell Nozzles:**
  - Dimensions for Shell Nozzles: Table 5.6
  - Dimensions for Shell Nozzles: Pipe, Plate, and Welding Schedules (SI): Table 5.7
  - Dimensions for Shell Nozzle Flanges: Table 5.8
- **Roof Manholes:**
  - Dimensions for Roof Manholes: Table 5-13
  - Standard figure of roof manhole: Figure 5.16
Tables and Figures

• **Drawoff Sump:**
  - Standard figure of Sump: Figure 5.21
  - Dimensions for Drawoff Sumps: Table 5.16

• **Platforms, Stairways and Walkways:**
  - Requirements for Platforms and Walkways: Table 5.17
  - Requirements for Stairways: Table 5.18
  - Rise, Run, and Angle Relationships for Stairways: Table 5.19

• **Grounding Lug:** Figure 5.23

• **Some Acceptable Column Base Details:** Figure 5.26
### Shell Openings

- **5.7.1.7**

  - Shell openings may be reinforced by the use of an insert plate/reinforcing plate combination or thickened insert plate per Figure 5.7b.
  
  - A rectangular insert plate or thickened insert plate shall have rounded corners (except for edges terminating at the tank bottom or at joints between shell courses) with a radius which is greater than or equal to the larger of 150 mm (6 in.) or 6t where t is the thickness of the shell course containing the insert plate or thickened insert plate.
  
  - The insert plate or thickened insert plate may contain multiple shell openings.
  
  - The thickness and dimensions of insert plate or thickened insert plate shall provide the reinforcing required per 5.7.2.
  
  - The periphery of thickened insert plates shall have a 1:4 tapered transition to the thickness of the adjoining shell material when the insert plate thickness exceeds the adjacent shell thickness by more than 3 mm (1/8 in.).
Shell Openings

• 5.7.2.1

Openings in tank shells larger than required to accommodate a NPS 2 flanged or threaded nozzle shall be reinforced.

• 5.7.2.3

Reinforcing plates for manholes, nozzles, and other attachments shall be of the same nominal composition (i.e. same ASME P-number and Group Number) as the tank part to which they are attached, unless approved otherwise by the Purchaser.
5.7.2.8

The allowable stresses for the attachment elements are:

- a) For outer reinforcing plate-to-shell and inner reinforcing plate-to-nozzle neck fillet welds: \( S_d \times 0.60 \).
- b) For tension across groove welds: \( S_d \times 0.875 \times 0.70 \)
- c) For shear in the nozzle neck: \( S_d \times 0.80 \times 0.875 \)

- \( S_d \) is the maximum allowable design stress (the lesser value of the base materials joined) permitted by 5.6.2.1 for carbon steel, or by Tables S.2a and S.2b for stainless steel.
- The throat of the fillet shall be assumed to be 0.707 times the length of the shorter leg.
Shell Openings

- 5.7.2.9
- When two or more openings are located so that the outer edges (toes) of their normal reinforcing-plate fillet welds are closer than eight times the size of the larger of the fillet welds, with a minimum of 150 mm (6 in.), they shall be treated and reinforced as follows noted in 5.7.2.9 a,b and c.

- 5.7.2.10
- Each reinforcing plate for shell openings shall be provided with a 6 mm (1/4 in.) diameter telltale hole. The hole shall be located on the horizontal centerline and shall be open to the atmosphere.
5.7.3 Spacing of Welds around Connections

5.7.3.1

a) The toe of the fillet weld around a non-reinforced penetration or around the periphery of a reinforcing plate, and the centerline of a butt-weld around the periphery of a thickened insert plate or insert plate, shall be spaced at least the greater of eight times the weld size or 250 mm (10 in.) from the centerline of any butt-welded shell joints, as illustrated in Figure 5.6, dimensions A or B.

b) The toe of the fillet weld around a non-reinforced penetration or around the periphery of a reinforcing plate, and the centerline of a butt-weld around the periphery of a thickened insert plate or insert plate, shall be spaced at least the greater of eight times the larger weld size or 150 mm (6 in.) from each other, as illustrated in Figure 5.6, dimension E.
• 5.7.3.4

Nozzles and manholes should not be placed in shell weld seams and reinforcing pads for nozzles and manholes should not overlap plate seams (i.e. Figure 5.9, Details a, c, and e should be avoided). If there is no other feasible option and the Purchaser accepts the design, circular shell openings and reinforcing plates (if used) may be located in a horizontal or vertical butt-welded shell joint provided that the minimum spacing dimensions are met and a radiographic examination of the welded shell joint is conducted. The welded shell joint shall be fully radiographed for a length equal to three times the diameter of the opening, but the weld seam being removed need not be radiographed. Radiographic examination shall be in accordance with 8.1.3 through 8.1.8.
• 5.7.5.1

Each manhole reinforcing plate shall be provided with a 6 mm (1/4 in.) diameter telltale hole (for detection of leakage through the interior welds). The hole shall be located on the horizontal centerline and shall be open to the atmosphere.

• 5.7.5.4

The gasket materials shall meet service requirements based on the product stored, maximum design temperature, and fire resistance. Gasket dimensions, when used in conjunction with thin-plate flanges described in Figure 5.7a, have proven effective when used with soft gaskets, such as non-asbestos fiber with suitable binder. When using hard gaskets, such as solid metal, corrugated metal, metal-jacketed, and spiral-wound metal, the gasket dimensions, manhole flange, and manhole cover shall be designed per API Standard 620, Section 3.20 and Section 3.21. See 4.9 for additional requirements.
5.7.5.6

The required minimum thickness of manhole cover plate and bolting flange shall be
the greater of the values computed by the following formulas:

\[ t_c = D_b \times \sqrt{\frac{\text{CYHG}}{S_d}} + CA \]

\[ t_f = t_c - 3 \]

- \( t_c \) is the minimum nominal thickness of cover plate (not less than 8), in mm;
- \( t_f \) is the minimum nominal thickness of bolting flange (not less than 6), in mm;
- \( D_b \) is the bolt circle diameter (see Table 5.5), in mm;
- \( C \) is the coefficient for circular plates and equals 0.3;
- \( \gamma \) is the water density factor 0.00981, in MPa/m;
- \( H \) is the design liquid level (see 5.6.3.2), in m;
- \( G \) is the specific gravity of stored product not less than 1.0;
- \( S_d \) is the design stress equal to 0.5 \( S_y \) (\( S_y \) is the yield strength equal to 205), in MPa;

NOTE: Materials with higher yield strength of 205 MPa may be used, but for thickness calculations \( S_y \) shall be less than or equal to 205 MPa, to maintain a leak tight bolted joint.

\( CA \) is the corrosion allowance, in mm.
EXAMPLE

using a 23 m tall tank with 500 mm manway.

\[
t_c = 667 \times \sqrt{\frac{0.3 \left( \frac{9.81}{1000} \right) 23 \times 1.0}{0.5 \times 205}} + 0 = 17.14 \text{ mm}
\]
Wind Load on Tanks (Overturning Stability)
Wind Load on Tanks (Overturning Stability)

Figure 5.27—Overturning Check for Unanchored Tanks

Wind uplift load

Internal pressure load

$D/2$

$H$

$H/2$ for uniform pressure on shell

Moments about shell to bottom Joint

Dead load ($DL$)

Liquid hold down weight ($w_a$)
5.11.1 Overturning stability shall be calculated using the wind pressures given in 5.2.1(k).

5.2.1 (K): The design wind speed (V) shall be either:

- the 3-sec gust design wind speed determined from ASCE 7-05 multiplied by \( \sqrt{\mathit{r}} \), Figure 6-1; or
- the 3-sec gust design wind speed determined from ASCE 7-10 for risk category specified by the Purchaser (Figure 26.5-1A, Figure 26.5-1B, or Figure 26.5-1C) multiplied by 0.78; or
- the 3-sec gust design wind speed specified by the Purchaser, which shall be for a 3-sec gust based on a 2 % annual probability of being exceeded [50-year mean recurrence interval].

The 3-sec gust wind speed used shall be reported to the Purchaser.
5.2.1 (K) Wind Load Calculation

1) Design wind pressure (PWS and PWR) using design wind speed (V): The design wind pressure on shell (PWS) shall be \(0.86 \text{kPa} \times \left(\frac{V}{190}\right)^2\), on vertical projected areas of cylindrical surfaces. The design wind uplift pressure on roof (PWR) shall be \(1.44 \text{kPa} \times \left(\frac{V}{190}\right)^2\) (see item 2) on horizontal projected areas of conical or doubly curved surfaces. These design wind pressures are in accordance with ASCE 7-05 for wind exposure Category C. As alternatives, pressures may be determined in accordance with:

- a) ASCE 7-05 (exposure category and importance factor provided by Purchaser);
  or
- b) ASCE 7-10 (exposure category and risk category provided by Purchaser) with either velocity multiplied by 0.78 or the ASCE 7-10 pressure multiplied by 0.6;
  or
- c) a national standard for the specific conditions for the tank being designed.
5.2.1 (K) Wind Load Calculation

- 2) The design uplift pressure on the roof (wind plus internal pressure) need not exceed 1.6 times the design pressure P determined in F.4.1.

- 3) Windward and leeward horizontal wind loads on the roof are conservatively equal and opposite and therefore they are not included in the above pressures.

- 4) Fastest mile wind speed times 1.2 is approximately equal to 3-sec gust wind speed (V).

Note:
ASCE 7-10 wind velocities now have LRFD load factors and risk category (importance factors) built in, whereas API 650 uses the working stress. The 0.78 factor applied to the ASCE 7-10 wind speed provides a conversion to working stress levels.
Unanchored tanks shall meet the requirements of 5.11.2.1 or 5.11.2.2.

When the requirements of 5.11.2 cannot be satisfied, anchor the tank per the requirements of 5.12.

- 5.11.2.1 Unanchored tanks, except supported cone roof tanks meeting the requirements of 5.10.4, shall satisfy all of the following uplift criteria:

1) \[0.6M_w + M_{Pi} < \frac{M_{DL}}{1.5} + M_{DLR}\]

2) \[M_w + F_p(M_{Pi}) < (M_{DL} + M_F)/2 + M_{DLR}\]

3) \[M_{ws} + F_p(M_{Pi}) < M_{DL}/1.5 + M_{DLR}\]
5.11.2.2 Unanchored tanks with supported cone roofs meeting the requirements of 5.10.4 shall satisfy the following criteria:

\[ M_{WS} + F_p (M_{Pi}) < M_{DL} / 1.5 + M_{DLR} \]
Wind Load on Tanks (Overturning Stability)

where

\( F_P \) is the pressure combination factor, see 5.2.2;

\( M_{Pi} \) is the moment about the shell-to-bottom joint from design internal pressure;

\( M_w \) is the overturning moment about the shell-to-bottom joint from horizontal plus vertical wind pressure;

\( M_{DL} \) is the moment about the shell-to-bottom joint from the nominal weight of the shell and roof structure supported by the shell that is not attached to the roof plate;

\( M_F \) is the moment about the shell-to-bottom joint from liquid weight;

\( M_{DLR} \) is the moment about the shell-to-bottom joint from the nominal weight of the roof plate plus any attached structural;

\( M_{WS} \) is the overturning moment about the shell-to-bottom joint from horizontal wind pressure.
5.11.2.3 \( w_L \) is the resisting weight of the tank contents per unit length of shell circumference based on a specific gravity (\( G \)) of 0.7 or the actual product specific gravity, whichever is less, and a height of one-half the design liquid height \( H \). \( w_L \) shall be the lesser of 70.4 HD for SI Units (0.45 HD for USC units) or the following:

\[
w_L = 70t_b \sqrt{(F_{by}GH)} \quad (\text{N/m})
\]
where

\[ F_{by} \] is the minimum specified yield stress of the bottom plate under the shell, in MPa (lbf/in.\(^2\));

\[ G \] is the actual specific gravity of the stored liquid or 0.7, whichever is less;

\[ H \] is the design liquid height, in meters (ft);

\[ D \] is the tank diameter, in meters (ft);

\[ t_b \] is the required corroded thickness of the bottom plate under the shell, in mm (inches), that is used to resist wind overturning. The bottom plate shall have the following restrictions:

1) The corroded thickness, \( t_b \), used to calculate \( w_L \) shall not exceed the first shell course corroded thickness less any shell corrosion allowance.

2) When the bottom plate under the shell is thicker due to wind overturning than the remainder of the tank bottom, the minimum projection of the supplied thicker annular ring inside the tank wall, \( L \), shall be the greater of 450 mm (18 in.) or \( L_b \), however, need not be more than \( 0.035D \).
1) The corroded thickness, \( t_b \), used to calculate \( wL \) shall not exceed the first shell course corroded thickness less any shell corrosion allowance.

2) When the bottom plate under the shell is thicker due to wind overturning than the remainder of the tank bottom, the minimum projection of the supplied thicker annular ring inside the tank wall, \( L \), shall be the greater of 450 mm (18 in.) or \( L_b \), however, need not be more than 0.035\( D \).

\[
L_b = 0.024 \ t_b \sqrt{\left( \frac{F_{by}}{GH} \right)} \leq 0.035 \ D \quad \text{(in meters)}
\]
Design data:
1. D = 6 m
2. H = 7.2 m
3. HILL = 6.7 m
4. Specific gravity = 1.483
5. C.A. = 3 mm

Course Width = 1800 mm

Bottom Plate: 6 mm + C.A. = 9 mm

Design wind velocity: 125 km/hr
Snow load: 0 kPa
DP = Full of liquid
DT = 85°C

MAT = A 283 C
Sd = 137 MPa
St = 154 MPa
Fy = 205 MPa

Shell Design (1-one foot method):

\[ t_n = \max \left( t_{d_1}, t_{t_1} \right) \]

\[ t_{d_1} = \frac{4.9 D (H-0.3) G + CA}{S_d} \]

\[ t_{t_1} = \frac{4.9 D (H-0.3)}{S_t} \]

\[ t_1 = \frac{4.9 D (H-0.3) G + CA}{S_d} = \frac{4.9 \times 6 \times (7.2-0.3) \times 11.483}{137} = 3.51 \text{ mm} \]

\[ t_{t_1} = \frac{4.9 D (H-0.3)}{S_t} = \frac{4.9 \times 6 \times (7.2-0.3)}{154} = 1.37 \text{ mm} \]

Selected \( t_{d_1} = 3.51 \text{ mm} \), \( t_{t_1} = 1.37 \text{ mm} \)

So, selected thickness = \( \max (t_{d_1}, t_{t_1}) = 5.19 \text{ mm} \)

Min API Std. thickness = 6 mm for first shell course
5 mm for other courses

AS PER 5.6.1.1

So, selected thickness = 15:6 mm
\[ \begin{align*}
    t_2 &= 4.9 \times 6 \times (7.2 - 1.2 - 0.3) \times 1.983 \div 137 + 3 = 4.623 \text{ mm} \\
    t_{t_2} &= 4.9 \times 6 \times (7.2 - 1.2 - 0.3) \div 154 = 0.97 \text{ mm} \\
    t_2 &= 5 \text{ mm}
\end{align*} \]

For other courses same procedure to be done.

So course \# 3 & 4 = 5 mm

**Weight calculation for shell**

\[ W_1 = \pi (D + \text{thk}) \times \text{thk} \times \text{Density} \times 1.04 \times \text{Shell height} \]

1st = \[ \pi (6 + 0.006) \times 0.006 \times 7850 \times 1.04 \times 1.8 \approx 1.66365 \text{ kg} \]

For other courses = \[ \pi (6 + 0.005) \times 0.005 \times 7850 \times 1.8 \times 1.04 \approx 1.386 \text{ kg} \]

So, total shell course weight is \( 51821.65 \text{ kg} \)

**Annular plate width & thk.**

Product stress = \( \frac{(td - CA)}{t_{\text{cor}}} \times (5d) = \frac{(5.19 - 3)}{3} (137) = 10001 \text{ MPa} \)

Hydrostatic test stress: \( (\frac{t_t}{t_{\text{nominal}}}) (5t) = \frac{1.37}{6} (154) = 35.1 \text{ MPa} \)
So, Stress in first shell course is 100 MPa
and thk of $t \leq 19 \rightarrow$ So, Annular plate thk. is $6 + 3 = 9$ mm

Annular plate width:

$$= \text{Max. } \left( \frac{600}{L} \right) + t_{\text{shell}} + \text{Overlap length (56)} + 50 \text{ mm}$$

$$= \text{Max. } \left( \frac{600}{563.07} \right) + 6 + 50 + 50 = 706 \text{ mm}$$

$$L = 2 \sqrt{\frac{t_b}{\frac{F_y}{2YGH}}} = 2 \times 9 \text{ mm} \times \sqrt{\frac{205}{2 \left( \frac{9.81}{1000} \right) \times 1.483 \times 7.2}}$$

$$L = 563.07 \text{ mm}$$

**Roof Calculation**

$$t = \frac{D}{4.85 \sin \theta \sqrt{\frac{B}{2.2}} + CA} \text{ or } 5 \text{ mm whichever is greater}$$

$$\beta = \text{Max. } \left[ \frac{D_L + (L_r) + F_{pe} P_e}{D_L + P_e + 0.4(L_r)} \right]$$
\[ D_2 = \text{weight of roof and any other attachment} \]
\[ \text{Roof weight: } \frac{R \cdot D^2}{4} \times \text{Density} \times \text{thk} \times 1.04 = \text{Density} \times \text{thk} \]
\[ \text{Roof Area} \]
\[ \frac{R \cdot D^2}{4} \]

So, \[ D_2 = 7850 \times 0.012 \text{ m} = 94.2 \times 0.01 = 0.95 \text{ kPa} = 1 \text{ kPa} \]

\[ \left\{ \begin{align*}
D_2 + 0.4 \cdot \text{P}e &= 1 \text{ kPa} + 1 \text{ kPa} + 0 = 2 \text{ kPa} \\
D_2 + 0.4 \cdot L_r + \text{P}e &= 1 \text{ kPa} + 0.4 \cdot 1 \text{ kPa} = 1.4 \text{ kPa}
\end{align*} \right. \]

So, \[ B(T) = 2 \text{ kPa} \]

\[ t_s \geq \frac{6}{4.8 \sin(12)} \sqrt{\frac{2}{2.2}} \leq 5.74 \text{ mm} \]

12 mm

12 mm
Participating area

\[
\text{Area}_p = \frac{P^2D^2}{8 \mu \tan \theta} = \frac{2 \times (6)^2}{8 \times (123) \times (0.21)} = 0.34 \text{ mm}^2
\]

the same diffusivity with \( \beta(\gamma) = 2 \text{ KPa} \)

\( \mu_a = 0.6 \mu_f = 0.6 \times 205 = 123 \text{ NPa} \)
\( \theta = 12^\circ \)

\textbf{Detail b}

Area as per Eq. (15) is: \( \text{Area} = A_{\text{shell}} + A_{\text{root}} + A_{\text{angle}} \)

\( A_{\text{shell}} = W_c \times t_s = 73.48 \text{ mm} \times 5 \text{ mm} = 367.42 \text{ mm}^2 \)

\( A_{\text{root}} = W_h \times t_h = 124.8 \text{ mm} \times 12 \text{ mm} = 1497.6 \text{ mm}^2 \)

\( A_{\text{angle}} = ? \)

\( A_{\text{shell}} + A_{\text{root}} > \text{Area}_p \rightarrow \text{So, angle} \)

\( W_c = 0.6 \sqrt{R_c} = 0.6 \sqrt{(5)(300)} = 73.48 \text{ mm} \)

\( W_h = \min \left[ 0.3 \sqrt{R_c} ; 300 \right] = \min \left[ 0.3 \sqrt{14429.2} \times 12 ; 300 \right] = 124.8 \text{ mm} \)

\( R_c = \frac{R_c}{\sin \theta} = \frac{3000}{\sin (12^\circ)} = 14429.2 \text{ mm} \)

\( \rightarrow \text{Could be Min size as per ADR E50} \)

\( 50 \times 50 \times 5 \)
WIND GIRDER CALCULATION

\[ H_1 = 9.47 + \sqrt{\left( \frac{4}{6} \right)^3 \left( \frac{190}{V} \right)^2} = 9.47 \left( \frac{5}{2} \right) \sqrt{\left( \frac{2}{6} \right)^3 \left( \frac{190}{150} \right)^2} \]

\[ V = 125 \text{ km/hr} \times 1.2 = 150 \text{ km/hr.} \]

\[ \text{as per ASCET} \]

\[ \Rightarrow H_1 = 5.848 \text{ m} \]

Transformed shell?

\[ W_{tr} = W \sqrt{\left( \frac{t_{mu}}{t_{uw}} \right)^5} \]

\[ W_{tr} = 1800 \sqrt{\left( \frac{5.3}{6.3} \right)^5} = 1800 \times \sqrt{\left( \frac{2}{3} \right)^5} = 1084.32 \text{ mN} \]

\[ W_{tr1,4} = 1800 \sqrt{\left( \frac{2}{2} \right)^5} = 1800 \]

\[ \Sigma W_{tr} = 6.484 \text{ mN} \]

**Since \( \Sigma W_{tr} \) is more than \( H_1 \), so one intermediate wind girder is required.**
Position of Wind Curb

The exact location can be calculated based on reverse formula and a ring will be placed at first course, but for more stability (as per API) we put this ring at the middle height of tank about therefore a ring will be placed at 4000 mm.

Size of Ring

\[ z = \frac{D^2 h_v (V)}{17} = \frac{6^2 (3.2) (150)}{17} = 4.22 \text{ cm}^2 \]

From Table 5.20A, detail C we choose 65x65x6.
WIND STABILITY

WIND PRESSURE:
- On shell = 0.86 kPa \( \left( \frac{150}{190} \right)^2 = 0.536 \) kPa
- On roof = 1.44 kPa \( \left( \frac{150}{190} \right)^2 = 0.997 \) kPa

WIND FORCE (SHEAR):
- On shell = \( P_w \times T \times D \times H = 72.74 \) N
- On roof = \( P_w \times R \times D^2 \times 4 = 25.36 \) N

WIND MOMENT:
\[
\left( F_s \times \frac{H}{2} + F_r \times \frac{D}{2} \right) = 261.86 \text{ N.m} + 76.08 \text{ N.m}
\]
\[
= 337.94 \text{ N.m}
\]

5.11.2.1:

1) \( 0.6 \cdot M_w + M_{ri} < M_{DL}/1.5 + M_{DLR} \)
2) \( M_w + F_p (M_{ri}) < (M_{DL} + M_{ri})/2 + M_{DLR} \)
3) \( M_{wS} + F_p (M_{ri}) < M_{DL}/1.5 + M_{DLR} \)
$M_w = 337.94 \text{ Nm}$

$F_p = 0.4$

$M_{p_i} = 0$

$M_{D2} = \text{Shell weight} \times \frac{D}{2} = 5821.65 \times 3 = 17464.95 \text{ Kg} \times \text{m}$

$M_{D2} = 171156.51 \text{ Nm}$

$M_{D2R} = 3046.97 \times 3 = 9140.93 \text{ Kg} \cdot \text{m} = 89581.15$

$M_F = \frac{M_{D2} \times D}{2} = 1145.13 \text{ Nm}$

$N_L = \text{Min} \left| \frac{70.6 \sqrt{(E_y G H)}}{170} \right| = 381.7 \text{ N}$

$70.4 \text{ H.D.} = 3041.28 \text{ N}$

1) $0.6 \times 337.94 + 0 < \frac{171156.51}{1.5} + 89581.15$ \text{ Pass!}$

2) $337.94 + 0 < \left( \frac{171156.51 + 1145.13}{2} \right) + 89581.15$ \text{ Pass!}$

3) \text{...... Pass!}$

So, Tank is Stable.
App. F (INTERNAL PRESSURE)
F.1.1 The maximum internal pressure for closed-top API Standard 650 tanks may be increased to the maximum internal pressure permitted (18 kPa [2.5 lbf/in.2]) gauge when the additional requirements of this Annex are met. This Annex applies to the storage of nonrefrigerated liquids (see also API 620, Annex Q and Annex R). For maximum design temperatures above 93 °C (200 °F), see Annex M.
Does tank have internal pressure? (1.1.1, 1.1.13, F.1.1, F.1.2, F.1.3, F.2, and F.8.1)

- Yes
  - Does internal pressure exceed weight of roof and attached structural? (1.1.1)
    - No: Basic Design
    - Yes: Does internal pressure exceed the weight of the shell, roof and attached structural? (F.1.2)
      - No: Basic Design plus Annex F.1 through F.7. Anchors for pressure alone not required. Do not exceed $P_{max}$. Limit roof/shell compression area per F.5.
      - Yes: Basic Design

- No: Basic Design
Yes

Provide anchors and conform to F.8.

Does internal pressure exceed 18 kPa (2.5 PSIG)? (F.1.3 and F.2)

No

API 650 with Annex F or API 620 shall be used.

Yes

Use API 620
• **F.2 Design Considerations**

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

The details of the roof-to-shell junction shall be in accordance with Figure F.2, in which the participating area resisting the compressive force is shaded with diagonal lines.
F.4 Maximum Design Pressure and Test Procedure

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

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

where

- \( P \) is the internal design pressure, in kPa;
- \( A \) is the area resisting the compressive force, as illustrated in Figure F.2, in mm\(^2\);
- \( F_y \) is the lowest minimum specified yield strength (modified for design temperature) of the materials in the roof-to-shell junction, in MPa;
- \( \theta \) is the angle between the roof and a horizontal plane at the roof-to-shell junction, in degrees;
- \( \tan \theta \) is the slope of the roof, expressed as a decimal quantity;
- \( D_{LR} \) is the nominal weight of roof plate plus any structural members attached to the roof plate, in N.
• F.4.2 For unanchored tanks, the maximum design pressure, limited by uplift at the base of the shell, shall not exceed the value calculated from the following equations as applicable unless further limited by F.4.3:

• For unanchored fixed roof tanks except supported cone roof tanks, the maximum design pressure ($P_{\text{max}}$) shall be the minimum of (3) cases:

\[
\begin{align*}
(1) & \quad \frac{\beta}{D^3} \left( \frac{M_{DL}}{1.5} + M_{DLR} - 0.6 M_w \right) \\
(2) & \quad \frac{\beta}{F_p \cdot D^3} \left( \frac{M_{DL} + M_F}{2} + M_{DLR} - M_w \right) \\
(3) & \quad \frac{\beta}{F_p \cdot D^3} \left( \frac{M_{DL}}{1.5} + M_{DLR} - M_{ws} \right)
\end{align*}
\]

For unanchored supported cone roof tanks:

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

\[ D \] is the tank diameter, m (ft);

\[ \beta \] is the conversion factor: for SI = \([8/(\pi \times 1000)]\), for USC = \([(8 \times 12)/(\pi \times 62.4)]\);

\[ F_p \] is the pressure combination factor, see 5.2.2;

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

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

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

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

\[ M_{w5} \] is the overturning moment about the shell-to-bottom joint from horizontal wind pressure, N \( \times \) m (ft \( \times \) lbf);

\[ P_{max} \] is the maximum design pressure kPa (inches of water).
\[ P \rightarrow \text{Limit by F.4.2} = P_{\text{max}} \rightarrow P_{\text{max}} < P_{f} \]
F.4 Maximum Design Pressure and Test Procedure

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

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

where

- \( P \) is the internal design pressure, in kPa;
- \( A \) is the area resisting the compressive force, as illustrated in Figure F.2, in mm\(^2\);
- \( F_y \) is the lowest minimum specified yield strength (modified for design temperature) of the materials in the roof-to-shell junction, in MPa;
- \( \theta \) is the angle between the roof and a horizontal plane at the roof-to-shell junction, in degrees;
- \( \tan \theta \) is the slope of the roof, expressed as a decimal quantity;
- \( D_{LR} \) is the nominal weight of roof plate plus any structural members attached to the roof plate, in N.
F.4.2 For unanchored tanks, the maximum design pressure, limited by uplift at the base of the shell, shall not exceed the value calculated from the following equations as applicable unless further limited by F.4.3:

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

\[
\begin{align*}
(1) \quad & \frac{\beta}{D^3} \left( \frac{M_{DL}}{1.5} + M_{DLR} - 0.6 M_w \right) \\
(2) \quad & \frac{\beta}{F_p \cdot D^3} \left( \frac{M_{DL} + M_F}{2} + M_{DLR} - M_w \right) \\
(3) \quad & \frac{\beta}{F_p \cdot D^3} \left( \frac{M_{DL}}{1.5} + M_{DLR} - M_w \right)
\end{align*}
\]

For unanchored supported cone roof tanks:

\[
P_{\text{max}} = \frac{\beta}{F_p \cdot D^3} \left( \frac{M_{DL}}{1.5} + M_{DLR} - M_w \right)
\]
where

\[ D \] is the tank diameter, m (ft);

\[ \beta \] is the conversion factor: for SI = \[8/(\pi \times 1000)\], for USC = \[((8 \times 12)/(\pi \times 62.4))\];

\[ F_p \] is the pressure combination factor, see 5.2.2;

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

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

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

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

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

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

\[ P_{\text{max}} \leq 0.8P_f \]
• **F.7 Calculated Failure Pressure**

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

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

where

- \( P_f \) is the calculated minimum failure pressure, in kPa;
- \( D_{LR} \) is the nominal weight of roof plate plus any attached structural, in N.
F.4.4 When the entire tank is completed, it shall be filled with water to the top angle or the design liquid level, and the design internal air pressure shall be applied to the enclosed space above the water level and held for 15 minutes. The air pressure shall then be reduced to one-half the design pressure, and all welded joints above the liquid level shall be checked for leaks by means of a soap film, linseed oil, or another suitable material. Tank vents shall be tested during or after this test.
F.8.3 After the tank is filled with water, the shell and the anchorage shall be visually inspected for tightness. Air pressure of 1.25 times the design pressure shall be applied to the tank filled with water to the design liquid height. The air pressure shall be reduced to the design pressure, and the tank shall be checked for tightness. In addition, all seams above the water level shall be tested using a soap film or another material suitable for the detection of leaks.

After the test water has been emptied from the tank (and the tank is at atmospheric pressure), the anchorage shall be checked for tightness. The design air pressure shall then be applied to the tank for a final check of the anchorage.
F.5 Required Compression Area at the Roof-to-Shell Junction

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

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

where

- \( A \) is the total required compression area at the roof-to-shell junction, in mm\(^2\);
- \( P_i \) is the design internal pressure, in kPa;
- \( D_{LR} \) is the nominal weight of roof plate plus any attached structural, in N.
F.6 Design of Roof Plates

- F.6.1 Minimum thickness of supported and self-supporting cone roofs under internal pressure shall be calculated as follows:
  
  - **NOTE 1** Thickness (t) of lap welded plates when controlled by internal pressure design shall not exceed 13 mm (1/2 in.) excluding corrosion allowance.
  
  - **NOTE 2** Calculated thickness (t) of roof plates shall not be less than that required under 5.10.4 for supported cone or less than that required under 5.10.5 for self-supporting cone roofs.

\[
t = \frac{(P \times R_s)}{\cos \alpha \times S_d \times E} + C_a
\]

where:

- \( t \) is the minimum roof thickness required for internal pressure in mm (in.);
- \( P \) is the internal Design pressure – minus effect of nominal roof dead load in kPa (lbf/in.²);
\( R_t \) is the nominal tank radius in m (in.);

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

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

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

\( E \) is the joint efficiency:

\[
E = 0.35 \text{ for full fillet lap welded plate from top side only},
\]

\[
E = 0.65 \text{ for full fillet lap welded plate from both sides},
\]

\[
E = 0.70 \text{ for full-penetration, complete-fusion butt welded plates with or without backing strip},
\]

\[
E = 0.85 \text{ for full-penetration, complete-fusion butt welded plates with spot radiography in accordance with 8.1.2.2},
\]

\[
E = 1.0 \text{ for full-penetration, complete-fusion butt welded plates with 100% full radiography};
\]

\( C_a \) is the corrosion allowance in mm (in.) as specified by the Purchaser (see 5.3.2).
F.6.2 Minimum thickness of self-supporting dome and umbrella roofs under internal pressure shall be calculated as follows:

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

where

- \( t \) is the minimum roof thickness required for internal pressure in mm (in.);
- \( \gamma \) is the Shape factor:
  - \( \gamma = 0.50 \) for dome roofs with spherical shape (double radius of curvature),
  - \( \gamma = 1.0 \) for umbrella roofs (single radius of curvature);
- \( P \) is the internal Design pressure – minus effect of nominal roof dead load in kPa (lbf/in²);
- \( R_R \) is the roof radius in m (in.);
- \( S_d \) is the allowable stress for the design condition per this Standard in MPa (lbf/in²);
- \( E \) is the joint efficiency:
  - \( E = 0.35 \) for full fillet lap welded plate from top side only,
The rules in F.6.1 and F.6.2 cannot cover all details of tank roof design and construction. With the approval of the Purchaser, the roof need not comply with F.6. The manufacturer shall provide a roof designed and constructed to be as safe as otherwise provided for in this standard.
• **F.8 Anchored Tanks with Design Pressures up to 18 kPa (2.5 psi) Gauge**

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

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

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

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

  c) The uplift produced by 1.5 times the calculated failure pressure (Pf in F.6) applied to the tank filled with the design liquid. The effective weight of the liquid shall be limited to the inside projection of the ringwall (Annex B type) from the tank shell. Friction between the soil and the ringwall may be included as resistance. When a footing is included in the ringwall design, the effective weight of the soil may be included.
App. E (SEISMIC DESIGN OF STORAGE TANKS)
AIMS

- Determining spectral acceleration parameters using ASCE 7 method
- Determining spectral acceleration parameters using peak ground acceleration
- Determining spectral acceleration parameters using site-specific response spectrum
- Calculating impulsive, convective and combined overturning moment and base shear
- Calculating anchorage ratio “J” and self-anchored annular plate
- Calculating hydrodynamic hoop stresses
- Calculating the overturning stability ratio
Seismic Use Group

- Seismic Use Group III
- Seismic Use Group II
- Seismic Use Group I
EC.3.1.1 Seismic Use Group III

Tanks assigned the SUG III designation are those whose function are deemed essential (i.e. critical) in nature for public safety, or those tanks that store materials that may pose a very serious risk to the public if released and lack secondary control or protection. For example, tanks serving these types of applications may be assigned SUG III unless an alternative or redundant source is available:

1) fire, rescue, and police stations;

2) hospitals and emergency treatment facilities;

3) power generating stations or other utilities required as emergency backup facilities for Seismic Use Group III facilities;

4) designated essential communication centers;

5) structures containing sufficient quantities of toxic or explosive substances deemed to be hazardous to the public but lack secondary safeguards to prevent widespread public exposure;

6) water production, distribution, or treatment facilities required to maintain water pressure for fire suppression within the municipal or public domain (not industrial).

It is unlikely that petroleum storage tanks in terminals, pipeline storage facilities and other industrial sites would be classified as SUG III unless there are extenuating circumstances.
EC.3.1.2  Seismic Use Group II

Tanks assigned the SUG II designation are those that should continue to function, after a seismic event, for public welfare, or those tanks that store materials that may pose a moderate risk to the public if released and lack secondary containment or other protection. For example, tanks serving the following types of applications may be assigned SUG II unless an alternative or redundant source is available:

1) power generating stations and other public utility facilities not included in Seismic Use Group III and required for continued operation;

2) water and wastewater treatment facilities required for primary treatment and disinfection for potable water.

EC.3.1.3  Seismic Use Group I

SUG I is the most common classification. For example, tanks serving the following types of applications may be assigned SUG I unless an alternative or redundant source is available:

1) storage tanks in a terminal or industrial area isolated from public access that has secondary spill prevention and control;

2) storage tanks without secondary spill prevention and control systems that are sufficiently removed from areas of public access such that the hazard is minimal.
Site Ground Motion

- Mapped ASCE 7 Methods
- Site-specific Spectral Response Accelerations
- Sites Not Defined By ASCE 7 Methods
EC.4 Site Ground Motion

The definition of the considered ground motion at the site is the first step in defining acceleration parameters and loads. The philosophy for defining the considered ground motion in the U.S. began changing about 1997. This new approach, which began with the evolution of the 1997 UBC and advanced through the efforts of the National Earthquake Hazard Reduction Program, was the basic resource for the new model building codes. Subsequent to the International Building Code 2000, ASCE 7 adopted the methods and is presently the basis for the US model building codes.

However, regulations governing seismic design for tank sites outside the U.S. may not follow this ASCE 7 approach. Therefore, this revision was written to be adaptable to these regulations. Consequently, there is no longer a definition of the “minimum” design ground motion based on US standards that applies to all sites regardless of the local regulations.

Historically, this Annex (and the U.S. standards) was based on ground motion associated with an event having a 10% probability of exceedance in 50 years. This is an event that has a recurrence interval of 475 years. In seismically active areas where earthquakes are more frequent, such as the west coast of the US, this was a reasonable approach. In regions where earthquakes are less frequent, engineers and seismologists concluded that the hazard was under-predicted by the 475 year event. Thus, the maximum considered ground motion definition was revised to a 2% probability of exceedance in 50 years, or a recurrence interval of about 2500 years. The economic consequences of designing to this more severe ground motion was impractical so a scaling factor was introduced based on over-strength inherently present in structures built to today’s standards. See the NEHRP Provisions for a more extensive discussion of this rationale.

The API Seismic Task Group considered setting the 475 year event as the “minimum” for application of this standard. Given the variations worldwide in defining the ground motion, it was decided that the local regulation should set the requirements. However, the owner/specifying engineer for the tank should carefully consider the risk in selecting the appropriate design motion in areas outside the U.S. The API Seismic Task Group suggests that the 475 year event be the minimum basis for defining the site ground motion for tanks.
EC.4.2.4 Site-Specific MCE Ground Motions

Figure EC.5 illustrates conceptually how these requirements might relate to define the site specific response spectrum.
EC.4.5  Structural Period of Vibration

EC.4.5.1  Impulsive Natural Period

To use the methods in this Annex, the impulsive seismic acceleration parameter is independent of tank system period unless a site-specific analysis or soil structure interaction evaluation is performed. The impulsive period of the tank is nearly always less than $T_s$, placing it on the plateau of the response spectra. Thus, the impulsive acceleration parameter is based directly on $S_{DS}$. For special circumstances, a simplified procedure was included in the Annex to determine the impulsive period which was taken from the following reference:


EC.4.5.2  Convective (Sloshing) Period

For convenience, the graphical procedure for determining the sloshing period, $T_c$, is included here. See Equation E.4.5.2-b and Figure EC.5.

$$T_c = K_s \sqrt{D}$$  \hspace{1cm} (E.4.5.2-b)

where

$D$ is the nominal tank diameter in ft;
E.2.2 Notations

- $A$  Lateral acceleration coefficient, $\%g$
- $A_c$  Convective design response spectrum acceleration parameter, $\%g$
- $A_f$  Acceleration coefficient for sloshing wave height calculation, $\%g$
- $A_i$  Impulsive design response spectrum acceleration coefficient, $\%g$
- $A_v$  Vertical earthquake acceleration parameter $= (2/3) \times 0.7 \times S_{DS} = 0.47 \times S_{DS}, \%g$
- $C_d$  Deflection amplification factor, $C_d = 2$
- $C_i$  Coefficient for determining impulsive period of tank system
\[ V = \sqrt{V_i^2 + V_c^2} \]

where

\[ V_i = A_i(W_s + W_r + W_f + W_i) \]

\[ V_c = A_c W_c \]
Impulsive spectral acceleration parameter, $A_i$:

$$A_i = S_{DS}(\frac{I}{R_{\text{wi}}}) = 2.5QF_aS_0(\frac{I}{R_{\text{wi}}})$$  \hspace{1cm} (E.4.6.1-1)

However, \hspace{0.5cm} A_i \geq 0.007  \hspace{1cm} (E.4.6.1-2)

and, for \hspace{0.5cm} S_1 \geq 0.6:

$$A_i \geq 0.5S_1(\frac{I}{R_{\text{wi}}}) = 0.625S_F(\frac{I}{R_{\text{wi}}})$$  \hspace{1cm} (E.4.6.1-3)

Convective spectral acceleration parameter, $A_c$:

When, $T_C \leq T_L$ \hspace{0.5cm} $A_c = K S_{D1}(\frac{T_t}{T_c})(\frac{I}{R_{\text{wc}}}) = 2.5KQF_aS_0(\frac{T_t}{T_c})(\frac{I}{R_{\text{wc}}}) \leq A_i$  \hspace{1cm} (E.4.6.1-4)

When, $T_C > T_L$ \hspace{0.5cm} $A_c = K S_{D1}(\frac{T_t}{T_c^2})(\frac{I}{R_{\text{wc}}}) = 2.5KQF_aS_0(\frac{T_t}{T_c^2})(\frac{I}{R_{\text{wc}}}) \leq A_i$  \hspace{1cm} (E.4.6.1-5)
App. E (SEISMIC DESIGN OF STORAGE TANKS)

- SDs
- I
- Rwi
- Rwc
- Q
- Fa
- Fv
- SO
- SD1
- Ts
- Tc
- K
- TL
### App. E (SEISMIC DESIGN OF STORAGE TANKS)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_0$</td>
<td>Mapped, maximum considered earthquake, 5% damped, spectral response acceleration parameter at a period of zero seconds (peak ground acceleration for a rigid structure), $%g$</td>
</tr>
<tr>
<td>$S_1$</td>
<td>Mapped, maximum considered earthquake, 5% damped, spectral response acceleration parameter at a period of one second, $%g$</td>
</tr>
<tr>
<td>$S_a$</td>
<td>The 5% damped, design spectral response acceleration parameter at any period based on mapped, probabilistic procedures, $%g$</td>
</tr>
<tr>
<td>$S_a^*$</td>
<td>The 5% damped, design spectral response acceleration parameter at any period based on site-specific procedures, $%g$</td>
</tr>
<tr>
<td>$S_{a0}^*$</td>
<td>The 5% damped, design spectral response acceleration parameter at zero period based on site-specific procedures, $%g$</td>
</tr>
<tr>
<td>$S_{D1}$</td>
<td>The design, 5% damped, spectral response acceleration parameter at one second based on the ASCE 7 methods, equals $Q F_v S_1$, $%g$</td>
</tr>
<tr>
<td>$S_{DS}$</td>
<td>The design, 5% damped, spectral response acceleration parameter at short periods ($T = 0.2$ seconds) based on ASCE 7 methods, equals $Q F_a S_5$, $%g$</td>
</tr>
<tr>
<td>$S_p$</td>
<td>Design level peak ground acceleration parameter for sites not addressed by ASCE methods. [See EC Example Problem 2 when using “Z” factor from earlier editions of API 650 and UBC. Since 475 year recurrence interval is basis of this peak ground acceleration, $Q = 1.0$ (no scaling).]</td>
</tr>
<tr>
<td>$S_s$</td>
<td>Mapped, maximum considered earthquake, 5% damped, spectral response acceleration parameter at short periods (0.2 sec), $%g$</td>
</tr>
<tr>
<td>$s_u$</td>
<td>Undrained shear strength, ASTM D2166 or ASTM D2850</td>
</tr>
</tbody>
</table>
tank (see E.4.5.1) using the 5% damped spectra, or the period may be assumed to be 0.2 seconds. \( A_c \) shall be based on the calculated convective period (see E.4.5.2) using the 0.5% spectra.

2) If no response spectra shape is prescribed and only the peak ground acceleration, \( S_A \) is defined, then the following substitutions shall apply:

\[
S_S = 2.5 \, S_P \quad (E.4.3-1)
\]

\[
S_1 = 1.25 \, S_P \quad (E.4.3-2)
\]
### Table E.4—Response Modification Factors for ASD Methods

<table>
<thead>
<tr>
<th>Anchorage system</th>
<th>$R_{wi}$ (impulsive)</th>
<th>$R_{wc}$ (convective)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Self-anchored</td>
<td>3.5</td>
<td>2</td>
</tr>
<tr>
<td>Mechanically-anchored</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>

### Table E.5—Importance Factor ($I$) and Seismic Use Group Classification

<table>
<thead>
<tr>
<th>Seismic Use Group</th>
<th>$I$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1.0</td>
</tr>
<tr>
<td>II</td>
<td>1.25</td>
</tr>
<tr>
<td>III</td>
<td>1.5</td>
</tr>
</tbody>
</table>
### Table E.1—Value of $F_a$ as a Function of Site Class

<table>
<thead>
<tr>
<th>Site Class</th>
<th>$S_z \leq 0.25$</th>
<th>$S_z = 0.50$</th>
<th>$S_z = 0.75$</th>
<th>$S_z = 1.0$</th>
<th>$S_z \geq 1.25$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>B</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>C</td>
<td>1.2</td>
<td>1.2</td>
<td>1.1</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>D</td>
<td>1.6</td>
<td>1.4</td>
<td>1.2</td>
<td>1.1</td>
<td>1.0</td>
</tr>
<tr>
<td>E</td>
<td>2.5</td>
<td>1.7</td>
<td>1.2</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>F</td>
<td>a</td>
<td>a</td>
<td>a</td>
<td>a</td>
<td>a</td>
</tr>
</tbody>
</table>

* Site-specific geotechnical investigation and dynamic site response analysis is required.

### Table E.2—Value of $F_y$ as a Function of Site Class

<table>
<thead>
<tr>
<th>Site Class</th>
<th>$S_1 \leq 0.1$</th>
<th>$S_1 = 0.2$</th>
<th>$S_1 = 0.3$</th>
<th>$S_1 = 0.4$</th>
<th>$S_1 \geq 0.5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>B</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>C</td>
<td>1.7</td>
<td>1.6</td>
<td>1.5</td>
<td>1.4</td>
<td>1.3</td>
</tr>
<tr>
<td>D</td>
<td>2.4</td>
<td>2.0</td>
<td>1.8</td>
<td>1.6</td>
<td>1.5</td>
</tr>
<tr>
<td>E</td>
<td>3.5</td>
<td>3.2</td>
<td>2.8</td>
<td>2.4</td>
<td>2.4</td>
</tr>
<tr>
<td>F</td>
<td>a</td>
<td>a</td>
<td>a</td>
<td>a</td>
<td>a</td>
</tr>
</tbody>
</table>

* Site-specific geotechnical investigation and dynamic site response analysis is required.
E.4.4 Modifications for Site Soil Conditions

The maximum considered earthquake spectral response accelerations for peak ground acceleration, shall be modified by the appropriate site coefficients, $F_a$ and $F_v$ from Table E.1 and Table E.2.

- Where the soil properties are not known in sufficient detail to determine the site class, Site Class D shall be assumed unless the authority having jurisdiction determines that Site Class E or F should apply at the site.
| ✓ SDs  |
| ✓ I    |
| ✓ Rwi  |
| ✓ Rwc  |
| ✓ Q    |
| ✓ Fa   |
| ✓ Fv   |
| ✓ S0   |
| ✓ SD1  |
| ❑ Ts   |
| ❑ Tc   |
| ❑ K (1.5 unless otherwise specified) |
| ❑ Ks   |
| ❑ TL   |
$T_0 : 0.2 \, FvS1 / FaSS$

$TS : FvS1 / FaSS$

\[ T_c = 1.8K_s\sqrt{D} \quad \text{(E.4.5.2-a)} \]

or, in USC units:

\[ T_c = K_s\sqrt{D} \quad \text{(E.4.5.2-b)} \]

\[ K_s = \frac{0.578}{\sqrt{\tanh\left(\frac{3.68H}{D}\right)}} \quad \text{(E.4.5.2-c)} \]
Ws : Total weight of tank shell and appurtenances, N (lbf)

Wr : Total weight of fixed tank roof including framing, knuckles, any permanent attachments and 10 % of the roof balanced design snow load, Sb, N (lbf)

Wf : Weight of the tank bottom, N

Wi : Effective impulsive portion of the liquid weight, N

Wc : Effective convective (sloshing) portion of the liquid weight, N
E.6.1.1 Effective Weight of Product

The effective weights $W_i$ and $W_c$ shall be determined by multiplying the total product weight, $W_p$, by the ratios $W_i/W_p$ and $W_c/W_p$, respectively, Equations E.6.1.1-1 through E.6.1.1-3.

When $D/H$ is greater than or equal to 1.333, the effective impulsive weight is defined in Equation E.6.1.1-1:

$$W_i = \frac{\tanh\left(0.866 \frac{D}{H}\right)}{0.866 \frac{D}{H}} W_p$$  \hspace{1cm} (E.6.1.1-1)

When $D/H$ is less than 1.333, the effective impulsive weight is defined in Equation E.6.1.1-2:

$$W_i = \left[1.0 - 0.218 \frac{D}{H}\right] W_p$$  \hspace{1cm} (E.6.1.1-2)

The effective convective weight is defined in Equation E.6.1.1-3:

$$W_c = 0.230 \frac{D}{H} \tanh\left(3.67 \frac{H}{D}\right) W_p$$  \hspace{1cm} (E.6.1.1-3)
Type of foundation

- Slab Moment
- Ringwall Moment
a) foundation from compacted soil (earth type foundation). This is most often applied scheme of foundation construction because it is cheapest and easiest for execution. It is made according to the scheme shown in standard API 650. It is used when the soil can bear the pressure of the upper steel construction and when the anchorage is not necessary. Even when there is small leak moving out of the soil is possible. It can leads to destruction of the tank. In this reason the diameter of the tank must be bigger than the diameter of the tank with not less then 1,8 m. Earth type foundation does not allow good leveling of the bottom i.e. of the shell of the tank. When they are used it is possible the uneven settlement which cause additional efforts in the tank's elements.

ref.: http://www.astanks.com
Earth type foundation
b) reinforced concrete ring which is not placed under the shell.

The tanks which are subject of this research are the above ground facilities. They are placed on 0,3 ÷ 1,2 m above the soil. This level difference is remarkable in the fuel oil tanks where pump always must be under the liquids ($\Delta h \geq 0,7m$). If the classical earth type foundation reaches this height the facility must occupy remarkable surface on the site. The reinforcing of such different leveled surfaces bears a risk for landslide (when the earth is covered by grass or asphalt) or it is slow, expensive and work consuming process (when the earth is paved).

In order to avoid this inconvenience appears the idea of small foundation ring between the ground and the bottom level which ring is a combination free sand pillow and reinforced concrete ring in the periphery. The proposed construction is similar to the API Std. 650, but the foundation ring is moved in the outside direction where it can not be influenced of the load of the shell and the tank roof upon it. When there is soil settlement under the tank, the reinforced concrete ring does not allow full drain of the water so that this solution is unfortunate. It should not be applied to the new build tanks.

ref.: http://www.astanks.com
Reinforced concrete ringwall foundation which is not placed under the shell
c) reinforced concrete ring wall foundation.

The trend in the tanks building shows that the volumes of the facility increase. Spatial steel construction of the tanks stands more flexible. In this reason bigger attention must be paid to the shell settlement and to the prevention measures. The use of the rigid reinforced concrete ring increase around the world. When the tanks are bigger the dimensions of the rings are: largeness not less then 0,6 m and height 1,5 - 2,0 m. This type foundation construction allows very good leveling of the periphery of the bottom and the shell which is positioned on it. The uneven settlement of the tank is limited. It is possible anchors to be put there.

ref.: http://www.astanks.com
d) reinforced concrete slab

They could be applied when the tanks are relatively small because this type of foundations is very expensive.

Thick concrete slabs are more favorable for upper steel structure. They do not allow the uneven settlement of the tank. The reinforced concrete slabs are very recommendable when the level of the underground water is high.

ref.: http://www.astanks.com
Basic parameters

$A_i$ & $A_c$

$V_i$ & $V_c$

$M_s$ & $M_r$
Ringwall Moment, $M_{rw}$:

$$M_{rw} = \sqrt{[A_i(W_iX_i + W_sX_s + W_rX_r)]^2 + [A_c(W_cX_c)]^2}$$

Slab Moment, $M_s$:

$$M_s = \sqrt{[A_i(W_iX_{is} + W_sX_s + W_rX_r)]^2 + [A_c(W_cX_{cs})]^2}$$
### App. E (SEISMIC DESIGN OF STORAGE TANKS)

<table>
<thead>
<tr>
<th>Equation</th>
<th>Description</th>
</tr>
</thead>
</table>
| Xi (E.6.1.2.1-1) & (E.6.1.2.1-2) | If $D/H \geq 1.33$  
|  | $X_i = 0.375H$  
|  | If $D/H < 1.33$  
|  | $X_i = \left[0.5 - 0.094\frac{D}{H}\right]H$  |
| Xs |  
|  | $X_s = \left[1.0 - \frac{\cosh\left(\frac{3.67H}{D}\right) - 1}{\frac{3.67H}{D}\sinh\left(\frac{3.67H}{D}\right)}\right]H$  |
| Xr | Height from the bottom of the tank shell to the roof and roof appurtenances center of gravity, m  |
| Xc (E.6.1.2.1-3) |  
|  | $X_c = \left[1.0 - \frac{\cosh\left(\frac{3.67H}{D}\right) - 1}{\frac{3.67H}{D}\sinh\left(\frac{3.67H}{D}\right)}\right]H$  |
### App. E (SEISMIC DESIGN OF STORAGE TANKS)

<table>
<thead>
<tr>
<th>Xis (E.6.1.2.2-1) &amp; (E.6.1.2.2-2)</th>
<th>$X_{is}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>If $D/H \geq 1.33$</td>
<td>$X_{is} = 0.375 \left[ 1.0 + 1.333 \left( \frac{0.866D}{H} \right) - 1.0 \right] H$</td>
</tr>
<tr>
<td>If $D/H &lt; 1.33$</td>
<td>$X_{is} = \left[ 0.500 + 0.060\frac{D}{H} \right] H$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Xcs (E.6.1.2.2-3)</th>
<th>$X_{cs}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$X_{cs} = \left[ 1.0 - \frac{\cosh \left( \frac{3.67H}{D} \right) - 1.937}{\frac{3.67H}{D} \sinh \left( \frac{3.67H}{D} \right)} \right] H$</td>
</tr>
</tbody>
</table>
### Table E.6—Anchorage Ratio Criteria

<table>
<thead>
<tr>
<th>Anchorage Ratio $J$</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J \leq 0.785$</td>
<td>No calculated uplift under the design seismic overturning moment. The tank is self-anchored.</td>
</tr>
<tr>
<td>$0.785 &lt; J \leq 1.54$</td>
<td>Tank is uplifting, but the tank is stable for the design load providing the shell compression requirements are satisfied. Tank is self-anchored.</td>
</tr>
<tr>
<td>$J &gt; 1.54$</td>
<td>Tank is not stable and cannot be self-anchored for the design load. Modify the annular ring if $L &lt; 0.035D$ is not controlling or add mechanical anchorage.</td>
</tr>
</tbody>
</table>
App. E (Anchorage Ratio, J)

\[ J = \frac{M_{rw}}{D^2 \left[ w_t (1 - 0.4A_v) + w_a - 0.4w_{int} \right]} \]

where

\[ w_t = \left[ \frac{W_s}{\pi D} + w_{rs} \right] \]
App. E (Anchorage Ratio, J)

\[ Av = \frac{2}{3} \times 0.7 \times SDS = 0.47 \text{ SDS, } \%g. \]

The vertical seismic acceleration parameter shall be taken as 0.47SDS, unless otherwise specified by the Purchaser. Alternatively, the Purchaser may specify the vertical ground motion acceleration. That acceleration shall be multiplied by 0.7 to obtain the vertical acceleration parameter, \( Av \).

\[ W_t = \text{Tank and roof weight acting at base of shell, N/m} \]

\[ W_{\text{int}} = \text{Calculated design uplift load due to product pressure per unit circumferential length, N/m} \]

\[ W_{\text{rs}} = \text{Roof load acting on the shell, including 10\% of the roof balanced design snow load, Sb, N/m} \]

\[ W_s = \text{Total weight of tank shell and appurtenances, N} \]
**App. E (Anchorage Ratio, J)**

\[ W_a = \text{Force resisting uplift in annular region, N/m} \]

For self-anchored tanks, a portion of the contents may be used to resist overturning. The anchorage provided is dependent on the assumed width of a bottom annulus uplifted by the overturning moment. The resisting annulus may be a portion of the tank bottom or a separate butt-welded annular ring. The overturning resisting force of the annulus that lifts off the foundation shall be determined by Equation E.6.2.1.1-1 except as noted below:

In SI units:

\[ w_a = 99t_a \sqrt{F_y H G_e} \leq 201.1 \; HDG_e \]  

(E.6.2.1.1-1a)

Equation E.6.2.1.1-1 for \( w_a \) applies whether or not a thickened bottom annulus is used. If \( w_a \) exceeds the limit of 201.1 \( HDG_e \), (1.28 \( HDG_e \)) the value of \( L \) shall be set to 0.035\( D \) and the value of \( w_a \) shall be set equal to 201.1 \( HDG_e \), (1.28 \( HDG_e \)). A value of \( L \) defined as \( L_s \) that is less than that determined by the equation found in E.6.2.1.1.2-1 may be used. If a reduced value \( L_s \) is used, a reduced value of \( w_a \) shall be used as determined below:

In SI units:

\[ w_a = 5742 \; HG_e L_s \]  

(E.6.2.1.1-2a)
E.6.2.2.1 Shell Compression in Self-Anchored Tanks

The maximum longitudinal shell compression stress at the bottom of the shell when there is no calculated uplift, \( J < 0.785 \), shall be determined by the formula:

In SI units:

\[
\sigma_c = \left( w_i (1 + 0.4A_w) + \frac{1.273M_{lw}}{D^2} \right) \frac{1}{1000t_s} \tag{E.6.2.2.1-1a}
\]

The maximum longitudinal shell compression stress at the bottom of the shell when there is calculated uplift, \( J > 0.785 \), shall be determined by the formula:

In SI units:

\[
\sigma_c = \left( \frac{w_i (1 + 0.4A_w) + w_a}{0.607 - 0.18667[J]^{23}} - w_a \right) \frac{1}{1000t_s} \tag{E.6.2.2.1-2a}
\]
E.6.2.2.2 Shell Compression in Mechanically-Anchored Tanks

- The maximum longitudinal shell compression stress at the bottom of the shell for mechanically-anchored tanks shall be determined by the formula:

\[ \sigma_c = \left( w_t (1 + 0.4A_v) + \frac{1.273M_{rw}}{D^2} \right) \frac{1}{1000 t_s} \]
E.6.2.2.3 Allowable Longitudinal Shell-Membrane Compression Stress in Tank Shell

When \( \frac{GHD^2}{t^2} \) is \( \geq 44 \) (SI units) (\( 10^6 \) USC units),

In SI units:

\[
F_c = \frac{83}{D} \frac{t_s}{D}
\]

(E.6.2.2.3-1a)

or, in USC units:

\[
F_c = 10^6 \frac{t_s}{D}
\]

(E.6.2.2.3-1b)

In SI units:

When \( \frac{GHD^2}{t^2} \) is less than 44:

\[
F_c = \frac{83t_s}{(2.5D)} + 7.5 \sqrt{(GH)} < 0.5F_{iy}
\]

(E.6.2.2.3-2a)

or, in USC units:

When \( \frac{GHD^2}{t^2} \) is less than \( 1 \times 10^5 \):

\[
F_c = 10^6 \frac{t_s}{(2.5D)} + 600 \sqrt{(GH)} < 0.5F_{iy}
\]

(E.6.2.2.3-2b)
Dynamic hoop tensile stresses due to the seismic motion of the liquid shall be determined by the following formulas:

\[
\sigma_T = \sigma_h \pm \sigma_s = \frac{N_h \pm \sqrt{N_i^2 + N_c^2}}{t}
\]

When vertical acceleration is specified.

\[
\sigma_T = \sigma_h \pm \sigma_s = \frac{N_h \pm \sqrt{N_i^2 + N_c^2 + (A_vN_h/2.5)^2}}{t}
\]
Dynamic hoop tensile stresses due to the seismic motion of the liquid shall be determined by the following formulas:

For $D/H \geq 1.333$:

$$N_i = 8.48 A_i G D H \left[ \frac{Y}{H} - 0.5 \left( \frac{Y}{H} \right)^2 \right] \tanh \left( 0.866 \frac{D}{H} \right)$$

For $D/H < 1.33$ and $Y < 0.75D$:

$$N_i = 5.22 A_i G D^2 \left[ \frac{Y}{0.75D} - 0.5 \left( \frac{Y}{0.75D} \right)^2 \right]$$

For $D/H < 1.333$ and $Y > 0.75D$:

$$N_i = 2.6 A_i G D^2$$
For all proportions of $D/H$:

In SI units:

$$N_e = \frac{1.85 A_c G D^2 \cosh \left[ \frac{3.68 (H - Y)}{D} \right]}{\cosh \left[ \frac{3.68 H}{D} \right]}$$
The maximum allowable hoop tension membrane stress for the combination of hydrostatic product and dynamic membrane hoop effects shall be the \textit{lesser of}:

- The basic allowable membrane in this standard for the shell plate material increased by 33 \%; or
- 0.9F_y times the joint efficiency where F_y is the lesser of the published minimum yield strength of the shell material or weld material.
Freeboard is required for SUG II and SUG III tanks. The height of the sloshing wave above the product design height can be estimated by:

\[ \delta_s = 0.42 \, DA_f \quad \text{(see Note c in Table E.7)} \]

For SUG I and II,

When, \( T_C \leq 4 \)
\[ A_f = KS_{D1}I\left(\frac{1}{T_C}\right) = 2.5KQF_aS_0I\left(\frac{T_S}{T_C}\right) \]

When, \( T_C > 4 \)
\[ A_f = KS_{D1}I\left(\frac{4}{T_C^2}\right) = 2.5KQF_aS_0I\left(\frac{4T_S}{T_C^2}\right) \]

For SUG III,

When, \( T_C \leq T_L \)
\[ A_f = KS_{D1}\left(\frac{1}{T_C}\right) = 2.5KQF_aS_0\left(\frac{T_S}{T_C}\right) \]

When, \( T_C > T_L \)
\[ A_f = KS_{D1}\left(\frac{T_L}{T_C^2}\right) = 2.5KQF_aS_0\left(\frac{T_S T_L}{T_C^2}\right) \]
### Table E.7—Minimum Required Freeboard

<table>
<thead>
<tr>
<th>Value of $S_{DS}$</th>
<th>SUG I</th>
<th>SUG II</th>
<th>SUG III</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{DS} &lt; 0.33g$</td>
<td>(a)</td>
<td>(a)</td>
<td>$\delta_5$ (c)</td>
</tr>
<tr>
<td>$S_{DS} \geq 0.33g$</td>
<td>(a)</td>
<td>$0.7\delta_5$ (b)</td>
<td>$\delta_5$ (c)</td>
</tr>
</tbody>
</table>

---

**a.** A freeboard of $0.7\delta_5$ is recommended for economic considerations but not required.

**b.** A freeboard equal to $0.7\delta_5$ is required unless one of the following alternatives are provided.

1. Secondary containment is provided to control the product spill.
2. The roof and tank shell are designed to contain the sloshing liquid.

**c.** Freeboard equal to the calculated wave height, $\delta_5$, is required unless one of the following alternatives are provided.

1. Secondary containment is provided to control the product spill.
2. The roof and tank shell are designed to contain the sloshing liquid.
ANCHOR BOLT DESIGN
### Anchor Bolt design

#### Table 5.21a—Uplift Loads (SI)

<table>
<thead>
<tr>
<th>Uplift Load Case</th>
<th>Net Uplift Formula, ( U ) (N)</th>
<th>Allowable Anchor Bolt or Anchor Strap Stress (MPa)</th>
<th>Allowable Shell Stress at Anchor Attachment (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Pressure</td>
<td>( P_t \times D^2 \times 785 ) ( - W_1 )</td>
<td>( \frac{5}{12} \times F_y )</td>
<td>( \frac{2}{3} F_y )</td>
</tr>
<tr>
<td>Test Pressure</td>
<td>( P_t \times D^2 \times 785 ) ( - W_3 )</td>
<td>( \frac{5}{9} \times F_y )</td>
<td>( \frac{5}{6} F_y )</td>
</tr>
<tr>
<td>Wind Load</td>
<td>( P_{WR} \times D^2 \times 785 + [4 \times M_{WS}/D] - W_2 )</td>
<td>0.8 ( \times F_y )</td>
<td>( \frac{5}{6} F_y )</td>
</tr>
<tr>
<td>Seismic Load</td>
<td>( [4 \times M_{rw}/D] - W_2 ) ( (1 - 0.4A_{PL}) )</td>
<td>0.8 ( \times F_y )</td>
<td>( \frac{5}{6} F_y )</td>
</tr>
<tr>
<td>Design Pressure(^a) + Wind</td>
<td>( [F_p \times (P_t + P_{WR}) \times D^2 \times 785] + [4 \times M_{WS}/D] - W_1 )</td>
<td>( \frac{5}{9} \times F_y )</td>
<td>( \frac{5}{6} F_y )</td>
</tr>
<tr>
<td>Design Pressure(^a) + Seismic</td>
<td>( [F_p \times P_t \times D^2 \times 785] + [4 \times M_{rw}/D] - W_1 ) ( (1 - 0.4A_{PL}) )</td>
<td>0.8 ( \times F_y )</td>
<td>( \frac{5}{6} F_y )</td>
</tr>
<tr>
<td>Frangibility Pressure(^b)</td>
<td>( [3 \times P_f \times D^2 \times 785] - W_3 )</td>
<td>( F_y )</td>
<td>( F_y )</td>
</tr>
</tbody>
</table>

- \( tb = U/N \)
- \( tb \) is the load per anchor;
- \( S \) (actual) = \( tb / \text{bolt area} \)
• **5.12.5** When anchor bolts are used, they shall have a corroded shank diameter of no less than 25 mm (1 in.).

• Carbon steel anchor straps shall have a nominal thickness of not less than 6 mm (1/4 in.) and shall have a minimum corrosion allowance of 1.5 mm (1/16 in.) on each surface for a distance at least 75 mm (3 in.), but not more than 300 mm (12 in.) above the surface of the concrete.

• N is the number of equally spaced anchors. If not equally spaced, then tb shall be increased to account for unequal spacing (a minimum of 4 anchors are required).

• The anchor center-to-center spacing measured along the tank circumference at shell outer diameter shall not exceed 3 m
FREE VENT DESIGN
API STANDARD 2000

Venting Atmospheric and Low-Pressure Storage Tanks

Nonrefrigerated and Refrigerated
API 2000 (Vent Design)

Inbreathing (Vacuum Relief)

VENTING REQUIREMENTS=Max

INBREATHING

OUTBREATHING

Outbreathing (Pressure Relief)
INBREATHING

- THERMAL
- MECHANICAL
### Table 1B—Normal Venting Requirements
(Nm³/hr of Air per Cubic Meter per Hour of Liquid Flow)

#### B. Metric Units

| Flash Point/Boiling Point | Inbreathing | | Outbreathing | | |
|--------------------------|-------------|-----------------|-----------------|
|                          | Liquid Movement Out | Thermal | Liquid Movement In | Thermal |
| Flash Point ≥ 37.8°C     | 0.94         | See Table 2B    | 1.01            | See Table 2B |
| Boiling Point ≥ 148.9°C  | 0.94         | “ ”             | 1.01            | “ ”         |
| Flash Point < 37.8°C     | 0.94         | “ ”             | 2.02            | “ ”         |
| Boiling Point < 149°C    | 0.94         | “ ”             | 2.02            | “ ”         |

*Data on flash point or boiling point may be used. Where both are available, use flash point (See Appendix A).*
<table>
<thead>
<tr>
<th>Tank Capacity (Cubic Meters)</th>
<th>Inbreathing (Vacuum) (Nm³/h)</th>
<th>Outbreathing Flash Point ≥ 37.8°C or Normal Boiling Point ≥ 148.9°C (Nm³/h)</th>
<th>Outbreathing Flash Point &lt; 37.8°C or Normal Boiling Point &lt; 148.9°C (Nm³/h)</th>
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Q = VA

V = Air velocity (5 ~ 15 m/s)

A = Cross section area of Nozzle