Vessels in chemical processing service are of two kinds: those substantially without internals and those with internals. The main functions of the first kinds, called drums or tanks, are intermediate storage or surge of a process stream for a limited or extended period or to provide a phase separation by settling. Their sizes may be established by definite process calculations or by general rules based on experience. The second category comprises the shells of equipment such as heat exchangers, reactors, mixers, fractionators, and other equipment whose housing can be designed and constructed largely independently of whatever internals are necessary. Their major dimensions are established by process requirements described in other chapters, but considerations of adequate strength of vessels at operating pressures and temperatures will be treated in this chapter.

The distinction between drums and tanks is that of size and is not sharp. Usually they are cylindrical vessels with flat or curved ends, depending on the pressure, and either horizontal or vertical. In a continuous plant, drums have a holdup of a few minutes. They are located between major equipment or supply feed or accumulate product. Surge drums between equipment provide a measure of stability in that fluctuations are not transmitted freely along a chain, including those fluctuations that are characteristic of control instruments of normal sensitivity. For example, reflux drums provide surge between a condenser and its tower and downstream equipment; a drum ahead of a compressor will ensure freedom from liquid entrainment and one ahead of a fired heater will protect the tubes from running dry; a drum following a reciprocating compressor will smooth out pressure surges, etc. Tanks are larger vessels, of several hours holdup usually. For instance, the feed tank to a batch distillation plant or a batch fractionator will hold the feed; and rundown tanks between equipment may provide several hours holdup as protection of the main storage from possible off-specification product and opportunity for local repair and servicing without disrupting the entire process.

Storage tanks are regarded as outside the process battery limits, on tank farms. Their sizes are measured in units of the capacities of connecting transportation equipment: 34,500 gal tank cars, 8000 gal tank trucks, etc., usually at least 1.5 times these sizes. Time variations in the supply of raw materials and the demand for the products influence the sizes and numbers of storage tanks.

Liquids stored at near atmospheric pressure are subject to breathing losses: As the tank cools during the night air is drawn in, then vaporization occurs as it warms up, and the vapor mixture is expelled as the tank warms up during the day. Volatile liquids such as gasoline consequently suffer a material loss and also a change in composition because of the selective loss of lighter constituents.

In order to minimize such effects, several provisions are made, for example:

1. A floating roof is a pad which floats on the surface of the stored liquid with a diameter of about a foot less than that of the tank. The annular space between the float and the shell may be sealed with one of several available methods.
2. An expansion roof allows thermal expansion of the vapor space. It rides with the changing vapor and is sealed with liquid in a double wall.
3. A bag of vapor resistant fabric is allowed to expand into a housing of much smaller diameter than that of the storage tank. This is a lower cost construction than either of the other two.

Weather resistant solids such as coal or sulfur or ores are stored in uncovered piles from which they are retrieved with power shovels and conveyors. Other solids are stored in silos. For short-time storage for process use, solids are stored in bins that are usually of rectangular cross section with cone bottoms and hooked up to process with conveyors. All aspects of the design of such equipment are covered in books by Reisner and Rothe (1971) and Stepanoff (1969).

18.1. DRUMS

Liquid drums usually are placed horizontal and gas-liquid separators vertical, although reflux drums with gas as an overhead product commonly are horizontal. The length to diameter ratio is in the range 2.5–5.0, the smaller diameters at higher pressures and for liquid–liquid settling. A rough dependence on pressure is

- a. For less than 1000 gal, use vertical tanks mounted on legs.
- b. Between 1000 and 10,000 gal, use horizontal tanks mounted on concrete foundation.
- c. Beyond 10,000 gal, use vertical tanks mounted on concrete foundations.

Liquids with high vapor pressures, liquefied gases, and gases at high pressure are stored in elongated horizontal vessels, less often in spherical ones. Gases are stored at substantially atmospheric pressure in gas holders with floating roofs that are sealed with liquid in a double wall. Liquefied gases are maintained at subatmospheric temperatures with external refrigeration or autorefrigeration whereby evolved vapors are compressed, condensed, cooled, and returned to storage.

The volume of a drum is related to the flow rate through it, but it depends also on the kinds of controls and on how harmful would be the consequences of downstream equipment running dry. Conventionally, the volume often is expressed in terms of the...
number of minutes of flow on a half-full basis. For many services, 5–10 min half-full is adequate but two notable exceptions are:

1. Fired heater feed surge drum for which the size is 10–30 min half-full.
2. Compressor feed liquid knockout drum which is made large enough to hold 10–20 min of liquid flow, with a minimum volume of 10 min worth of gas flow rate.

Other major services require more detailed consideration, as follows.

18.2. FRACTIONATOR REFLUX DRUMS

Commonly their orientation is horizontal. When a small amount of a second liquid phase (for example, water in an immiscible organic) is present, it is collected in and drawn off a pot at the bottom of the drum. The diameter of the pot is sized on a linear velocity of 0.5 ft/sec, which is a minimum of 16 in dia in drums of 4–8 ft dia, and 24 in. in larger sizes. The minimum vapor space above the high level is 20% of the drum diameter or 10 in (Sigales, 1975).

A method of sizing reflux drums proposed by Watkins (1967) is based on several factors itemized in Table 18.1. A factor $F_1$ is applied to the net overhead product going downstream, then instrument factors $F_1$ and labor factors $F_2$ which are added together and applied to the weighted overhead stream, and finally a factor $F_3$ is applied, which depends on the kind and location of level indicators. When $L$ is the reflux flow rate and $D$ the overhead net product rate, both in gpm, the volume of the drum (gal) is given by

$$V_d = 2F_3(F_1 + F_2)(L + F_3D) \text{ gal, full.} \quad (18.1)$$

For example, with $L = 400 \text{ gpm}$ and $D = 200 \text{ gpm}$, at average conditions $F_1 = 1$, $F_2 = 1.5$, $F_3 = 3$, $F_3 = 1.5$, and

$$V_d = 2(1.5)(1 + 1.5)(400 + 3(200)) = 7500 \text{ gal, full}$$

<table>
<thead>
<tr>
<th>TABLE 18.1 Factors for Sizing Reflux Accumulators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation</td>
</tr>
<tr>
<td>-----------</td>
</tr>
<tr>
<td>FRC</td>
</tr>
<tr>
<td>LRC</td>
</tr>
<tr>
<td>TRC</td>
</tr>
</tbody>
</table>

b. Factor $F_3$ on the Net Overhead Product Flow to External Equipment

<table>
<thead>
<tr>
<th>Operating Characteristics</th>
<th>$F_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Under good control</td>
<td>2.0</td>
</tr>
<tr>
<td>Under fair control</td>
<td>3.0</td>
</tr>
<tr>
<td>Under poor control</td>
<td>4.0</td>
</tr>
<tr>
<td>Feed to or from storage</td>
<td>1.25</td>
</tr>
</tbody>
</table>

c. Factor $F_4$ for Level Control

<table>
<thead>
<tr>
<th>Level Indicator</th>
<th>$F_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Board-mounted level recorder</td>
<td>1.0</td>
</tr>
<tr>
<td>Level indicator on board</td>
<td>1.5</td>
</tr>
<tr>
<td>Gage glass at equipment only</td>
<td>2.0</td>
</tr>
</tbody>
</table>

(Watkins, 1967).

Vessels for the separation of two immiscible liquids usually are made horizontal and operate full, although some low rate operations are handled conveniently in vertical vessels with an overflow weir for the lighter phase. The latter mode also is used for particularly large flows at near atmospheric pressures, as in the mixer-settler equipment of Figure 3.19. With the usual $L/D$ ratio of three or more, the travel distance of droplets to the separated phase is appreciably shorter in horizontal vessels.

Since the rise or fall of liquid droplets is interfered with by lateral flow of the liquid, the diameter of the drum should be made large enough to minimize this adverse effect. A rule based on the Reynolds number of the phase through which the movement of the liquid drops occurs is proposed by Hooper and Jacobs (1979). The Reynolds number is $D_hu_p/\mu$, where $D_h$ is the hydraulic diameter and $u$ is the linear velocity of the continuous phase. The rules are:

<table>
<thead>
<tr>
<th>Reynolds Number</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than 5000</td>
<td>little problem</td>
</tr>
<tr>
<td>5000–20,000</td>
<td>some hindrance</td>
</tr>
<tr>
<td>20,000–50,000</td>
<td>major problem may exist</td>
</tr>
<tr>
<td>Above 50,000</td>
<td>expect poor separation</td>
</tr>
</tbody>
</table>

The jet effect of an inlet nozzle also may interfere with the phase separation. Ideally the liquid should be introduced uniformly over the cross section, but a baffle at the inlet nozzle may reduce such a disturbance adequately. More elaborate feed diffusers sometimes may be worthwhile. Figure 18.1 shows a perforated baffle.

Fall or rise of droplets of one liquid in another is represented closely by Stokes law,

$$u = g_c(\rho_2 - \rho_1)d^2/18\mu. \quad (18.2)$$

In common units,

$$u = 9.97(10^4)(\rho_2 - \rho_1)d^2/\mu, \quad \text{ft/min,} \quad (18.3)$$

where the $\rho_i$ are specific gravities, $d$ is the droplet diameter (ft), and $\mu$ is the viscosity of the continuous phase (cP).

The key property is the droplet diameter, of which many studies have been made under a variety of conditions. In agitated vessels, experience shows that the minimum droplet diameters are in the range of 500–5000 $\mu$m. In turbulent pipeline flow, Middleman (1974) found that very few droplets were smaller than 500 $\mu$m. Accordingly, for separator design a conservative value is 150 $\mu$m, which also has been taken as a standard in the API Manual on Disposal of Refinery Wastes (1969). With this diameter,

$$u = 2.415(\rho_2 - \rho_1)/\mu, \quad \text{ft/min.} \quad (18.4)$$

Which phase is the dispersed one can be identified with the.
**Figure 18.1.** Drums for distillation tower reflux and for reciprocating compressor surge. (a) A reflux drum with a pot for accumulation and removal of a heavy phase. The main liquid is removed on level control through a vortex breaker. When the pot is large enough, it can accommodate an interface control for automatic drainage; otherwise the drain valve is hand set and monitored by an operator. (b) Arrangement of a surge drum for eliminating the high frequency response of a reciprocating compressor. Details are given by Ludwig (Applied Process Design for Chemical and Petrochemical Plants, Gulf, Houston, 1983, Vol. 3).

The rate of separation of liquid phases can be enhanced by shortening the path through which the droplets need rise or fall or by increasing their diameters. Both effects are achieved by forcing the flow between parallel flat or crimped plates or through tower packing or through a mass of packed fibers. The materials should be wetted by the disperse phase and preferably rough. Fine droplets will impinge on the surfaces and will grow by accretion of other droplets. The separator in such cases will consist of a coalescing section and an open section where the now enlarged droplets can separate freely. Figure 18.3 is of a separator equipped with a coalescer that is especially suited to the removal of relatively small quantities of dispersed liquid. Cartridge-type coalescers are described by Redmon (1963). Packed separators have been studied by Davies, Jeffrys, and Azzaf (1972) and the subject is reviewed by Laddha and Degaleesan (1983). Coalescence also can be induced electrically, a process that is used widely for the precipitation of brine from crude oils. Proprietary equipment is available for this purpose. The subject is discussed by Waterman (1965) and in detail by Fronczak (1983).

**OTHER METHODS**

Very fine dispersions can be separated effectively with disk-type centrifuges. Commercial units have capacities of 5–500 gpm and are capable of removing water from hydrocarbons down to the ppm range. A mild centrifugal action is achieved in hydrocyclones. They have been studied for liquid–liquid separation by Sheng, Welker, and Sliepcevich (1974), but their effectiveness was found only modest. The use of hydrocyclones primarily for the recovery of solid particles from liquids is described in the book of Bradley (1965). A symposium on coalescence has papers by Belk (1965), Jordan (1965), Landis (1965), and Waterman (1965).

**18.4. GAS–LIQUID SEPARATORS**

Droplets of liquid are removed from a gas phase by three chief methods:

1. Settling out under the influence of gravity.
2. Settling out under centrifugal action.
3. Impingement and coalescence on solid surfaces followed by settling.

Available methods for the design of liquid separators are arbitrary in some respects but can be made safe economically. Figure 18.4 illustrates some of these methods.

**DROPLET SIZES**

The period of time needed for settling out depends on the size distribution of droplets and the required completeness of removal. Under most conditions the droplet diameter is an elusive quantity. A few observations are mentioned by York (1983). Garner et al. (1954) found 95% of evaporator entrainment to be smaller than 18–25 μm. From spray nozzles the droplets are 90 wt % greater than 20 μm. Spray disks made droplet diameters in the range 100–1000 μm. Sprays resulting from splashing and pickup by vapors off condensed liquid films are as large as 5000 μm. Some mists are very fine, however; those in sulfuric acid plants are mostly less than 10 μm, and in some equipment 50 wt % are less than 1 μm (Duros and Kennedy, 1978). On the whole, sprays in process equipment usually are greater than 20 μm, mostly greater than 10 μm.

The amount of entrainment has been studied mostly in distillation equipment. Figure 18.5 summarizes some of these data, and they are applied in Example 18.2. Equation 18.11 incorporates entrainment data indirectly.

A common belief is that 95% of entrainment can be removed in economically sized gravity separators, in excess of 99% with wire

\[
\psi = \frac{Q_L}{Q_H} \left( \frac{P_L + H}{P_H} \right)^{0.3}
\]

(18.5)

with the statements of this table (Selker and Schleicher, 1965):

<table>
<thead>
<tr>
<th>ψ</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;0.3</td>
<td>light phase always dispersed</td>
</tr>
<tr>
<td>0.3–0.5</td>
<td>light phase probably dispersed</td>
</tr>
<tr>
<td>0.5–2.0</td>
<td>phase inversion probable, design for worst case</td>
</tr>
<tr>
<td>2.0–3.3</td>
<td>heavy phase probably dispersed</td>
</tr>
<tr>
<td>&gt;3.3</td>
<td>heavy phase always dispersed</td>
</tr>
</tbody>
</table>

These relations are utilized in Example 18.1 and the resulting design is represented on Figure 18.2.

**COALESCENCE**

The rate of separation of liquid phases can be enhanced by shortening the path through which the droplets need rise or fall or by increasing their diameters. Both effects are achieved by forcing the flow between parallel flat or crimped plates or through tower packing or through a mass of packed fibers. The materials should be wetted by the disperse phase and preferably rough. Fine droplets will impinge on the surfaces and will grow by accretion of other droplets. The separator in such cases will consist of a coalescing section and an open section where the now enlarged droplets can separate freely. Figure 18.3 is of a separator equipped with a coalescer that is especially suited to the removal of relatively small quantities of dispersed liquid. Cartridge-type coalescers are described by Redmon (1963). Packed separators have been studied by Davies, Jeffrys, and Azzaf (1972) and the subject is reviewed by Laddha and Degaleesan (1983). Coalescence also can be induced electrically, a process that is used widely for the precipitation of brine from crude oils. Proprietary equipment is available for this purpose. The subject is discussed by Waterman (1965) and in detail by Fronczak (1983).

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A common belief is that 95% of entrainment can be removed in economically sized gravity separators, in excess of 99% with wire
**Example 18.1**  
Separation of Oil and Water

Find the dimensions of a drum for the separation of oil and water at these conditions:

- Oil at 180 cfh, sp gr = 0.90, viscosity = 10 cP.
- Water at 640 cfh, sp gr = 1.00, viscosity = 0.7 cP.

Take a droplet size to be 150 µm (0.0005 ft) and that the holdup in the tank is in the same proportions as in the feed. The geometry of the cross section:

\[
A_1 = \frac{180\pi}{120} D^2 = \frac{D^2}{8} (\theta - \sin \theta), \\
\Rightarrow \theta = 2.192 \text{ rad}, \\
A_2 = 0.7805 \frac{\pi}{4} D^2 = 0.6130D^2, \\
L = D \sin(\theta/2) = 0.8894D, \\
S_2 = D \left( \frac{\pi - \theta}{2} \right) = 2.0456D.
\]

Hydraulic diameter of heavy liquid

\[
D_h = \frac{4A_2}{L + S_2} = \frac{4(0.6130D)}{0.8894 + 2.0456} = 0.8354D.
\]

The dispersion discriminant is

\[
\psi = \frac{Q_L (\rho_L \mu_L)}{Q_H (\rho_H \mu_L)} = \left( \frac{180}{640} \right) \left( \frac{0.9}{0.7} \right)^{0.3} = 0.123 < 0.30.
\]

Therefore, oil is the dispersed phase:

\[
N_{Re} = \frac{D_h \mu}{\mu} = \frac{D \rho}{\mu} \frac{Q}{\frac{4}{3} \pi D^3} = \frac{(62.4)(640)(0.8354)}{42(0.7)\pi} \frac{D}{D} = 25.076.
\]

Velocity of rise:

\[
u_r = \frac{2.492(1.00 - 0.90)}{0.7} = 0.356 \text{ ft/min}.
\]

Time of rise:

\[
t = \frac{0.7286D}{0.356} = 2.0466D \text{ min}.
\]

Forward velocity:

\[
u_F = \frac{QH}{A_2} = \frac{640}{60(0.6130D^2)} = \frac{17.40}{D^2} \text{ ft/min}.
\]

Flow distance:

\[
L_t = \frac{vu_F}{t} = \frac{2.0466D}{0.356} = 5.71 \text{ ft}.
\]

The tangent to tangent length of the drum will be approximately 24 in. greater than \( L_t \) to accommodate inlet and outlet nozzles and baffles.

The Reynolds number identifies the quality of the separation, \( N_{Re} < 5000 \) being good.

Some trials are

<table>
<thead>
<tr>
<th>( D (\text{ft}) )</th>
<th>( N_{Re} )</th>
<th>( t )</th>
<th>( u_r )</th>
<th>( L_t (\text{ft}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>5015</td>
<td>10.23</td>
<td>0.696</td>
<td>7.12</td>
</tr>
<tr>
<td>3.5</td>
<td>7165</td>
<td>7.16</td>
<td>1.420</td>
<td>10.17</td>
</tr>
<tr>
<td>3</td>
<td>8356</td>
<td>6.14</td>
<td>1.933</td>
<td>11.87</td>
</tr>
</tbody>
</table>

A vessel \( 5 \times 9 \) ft would give excellent separation; \( 3 \times 14 \) ft might be acceptable. A sketch of the proposed drum is in Figure 18.1.

Mesh pads and other solid surfaces on which impingement and coalescence are forced, and approaching 100% in scrubbers and high speed centrifuges.

**Rate of Settling**

The terminal or maximum settling velocity of a small droplet or particle in a gas is governed by one of Newton's equations.

\[
u = \sqrt{\frac{g \left( \rho - \rho_e \right)}{18 \mu}}. \tag{18.6}
\]

In laminar flow the friction factor becomes a simple function of the Reynolds number,

\[
f = \frac{2}{\sqrt{Re}}. \tag{18.7}
\]

When this substitution is made, the falling velocity becomes

\[
u = \frac{g_e (\rho - \rho_e)}{D^2 / 18 \mu}, \tag{18.2'}
\]

which is Stokes' equation. In view of the uncertainties with which droplet sizes are known in practical situations, Stokes equation usually is regarded as sufficiently descriptive of settling behavior. For example, it predicts that 100 µm droplets of water fall at the rate of \( 1.0 \text{ ft/sec} \) in atmospheric air.

Another approximation of Newton's equation is written

\[
u = \frac{K \rho / \rho_e - 1}, \tag{18.8}
\]

where the coefficient \( K \) depends on the system. For the 100 µm droplets of water in air just cited, the coefficient becomes
18.4. GAS-LIQUID SEPARATORS

Figure 18.2. A design of an oil-water separator for the conditions of Example 18.1, showing particularly the diffuser at the inlet nozzle and baffles at the outlets. (Hooper and Jacobs, 1979).

Figure 18.3. Drums with coalescers for assisting in the separation of small amounts of entrained liquid. (a) A liquid–liquid separating drum equipped with a coalescer for the removal of small amounts of dispersed phase. In water–hydrocarbon systems, the pot may be designed for 0.5 ft/sec (Facet Enterprises, Industrial Division). (b) An oil–water separator with corrugated plate coalescers (General Electric Co.).

\[ K = 0.035, \text{ and for other sizes it varies as the square of the diameter.} \]

EMPTY DRUMS

The cross section of a vertical settling drum is found from the vapor rate and the allowable linear velocity with the equation

\[ u = 0.14\sqrt{\frac{\rho_v}{\rho_g}} - 1, \text{ ft/sec}, \]  \hspace{1cm} (18.9)

in which the coefficient of Eq. (18.8) has been evaluated for 200 psig. The vertical dimension is more arbitrarily established. The liquid holdup is determined as in Section 18.2 and Table 18.1. For the vapor space, Watkins (1967) proposes the rules illustrated in Figure 18.6. When the calculated length to diameter ratio comes out less than 3, the length is increased arbitrarily to make the ratio 3; when the ratio comes out more than 5, a horizontal drum is preferably employed. Rules for horizontal drums also are shown on Figure 18.6. The vapor space is made a minimum of 20% of the drum volume which corresponds to a minimum height of the vapor space of 25% of the diameter, but with the further restriction that this never is made less than 12 in. When a relatively large amount of liquid must be held up in the drum, it may be advisable to increase the fraction of the cross section open to the vapor.

The diameter again is figured from the volumetric rate of the vapor and the linear velocity from Eq. (18.9). Since the upward drag of the vapor is largely absent in a horizontal drum, however, the coefficient \( K \) often is raised by a factor of 1.25. Example 18.3 deals with the design of both kinds of drums.

WIRE MESH PAD DEENTRAINERS

Pads of fine wire mesh induce coalescence of impinging droplets into larger ones, which then separate freely from the gas phase. Tower packings function similarly but are less effective and more difficult to install. The pads are made of metal wires or plastic strands or fiber glass. These data apply to stainless steel construction:

<table>
<thead>
<tr>
<th>Efficiency Type</th>
<th>Efficiency (%)</th>
<th>Pressure</th>
<th>Vacuum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>99.0</td>
<td>5-7</td>
<td>65</td>
</tr>
<tr>
<td>Standard</td>
<td>99.5</td>
<td>9</td>
<td>85</td>
</tr>
<tr>
<td>High</td>
<td>99.9</td>
<td>12</td>
<td>115</td>
</tr>
<tr>
<td>Very high</td>
<td>99.9</td>
<td>13-14</td>
<td>120</td>
</tr>
</tbody>
</table>

A pad thickness of 4 in. is minimum, 6 in. is popular, and up to 12 in. may be required for fine mists.

The values of \( K \) in the preceding table are with a standard disengaging height of 10 in. The effect of other heights \( h \) is given by the equation

\[ K = 0.021 + 0.0325h, \hspace{1cm} 3 \leq h \leq 12, \] \hspace{1cm} (18.10)

with a maximum value of 0.40. This relation is for standard efficiency pads. Lower values can be expected in aqueous systems where the surface tension has been reduced by surfactants.

When the pad is installed in a vertical or inclined position, the values of \( K \) should be taken \( \frac{2}{3} \) of the horizontal ones.

At high liquid rates droplets tend to be reentrained and the pad may become flooded. Some data obtained by Poppele (1958) are cited by York (1983, p. 194). A graphical correlation credited to the Fluor Co. is represented by Branan (1983, p. 67) by the equation

\[ K = -0.0073 + 0.263 \frac{x^{1.394}}{x^{0.573}}, \hspace{1cm} 0.04 \leq x \leq 6.0, \] \hspace{1cm} (18.11)
where $x$ is a function of the weight flow rates and densities of the phases

$$x = \frac{W_j}{W_v} \sqrt{\rho_v/\rho_L}.$$  (18.12)

Good performance can be expected at velocities of 30–100% of those calculated with the given $K_s$. Flooding velocities are at 120–140% of the design rates. At low velocities the droplets drift through the mesh without coalescing. A popular design velocity is about $75\%$ of the allowable. Some actual data of the harmful effect of low velocities were obtained by Carpenter and Othmer (1955); they found, for example, that $99\%$ of $6\mu m$ droplets were removed at $6.8$ ft/sec, but $99\%$ of $8\mu m$ at the lower velocity of $3.5$ ft/sec.

Pressure drop in pads usually is small and negligible except at flooding; the topic is discussed by York (1983).

In existing drums or when the drum size is determined primarily by the required amount of liquid holdup, the pad dimensions must conform to the superficial velocities given by the design equation. This may necessitate making the pad smaller than the available cross section of the drum. Figure 18.7 shows typical installations. On the other hand, when the pad size is calculated to be greater than the available cross section and there develops a possibility of reentrainment of large droplets from the exit surface of the pad, a downstream settling drum or a high space above the mesh can be provided.

Good design practice is a disengaging space of 6–18 in., the more the better, ahead of the pad and 12 in. above the pad. Other details are shown on Figure 18.8. A design is provided in Example 18.4.

18.5. CYCLONE SEPARATORS

In addition to those already discussed, a variety of proprietary and home-made devices can remove entrainment more or less effectively. Some of them are represented on Figure 18.8.

a. A simple change of direction and impingement on the walls of the drum.

b. Impingement on a baffle.

c. Tangential inlet at high velocity and change of direction.

d. Multiple baffles, without or with coarse spray irrigation.

e. A pipeline deentrainer.

The capacity and effectiveness of proprietary devices such as items c to e cannot be estimated from general knowledge, but manufacturers usually claim that they can be sized to remove $99\%$ of $8\mu m$ droplets or particles. “Separators, entrainment” is an entry in the index of the Chemical Engineering Catalog which is a guide to manufacturers who may be consulted about the performance of their equipment.

In cyclone separators the gas enters tangentially at a high velocity, rotates several times, and leaves through a central pipe. Such equipment has been studied widely, particularly for the removal of dusts and catalyst fines in fluidized bed systems. The literature is reviewed by Rietema and Verver (1961), Maas (1979), Zenz (1982), and Semrau (1984).

Typical cyclone dimension ratios are indicated on Figure 18.9. For liquid knockout the bottom head often is made dished as on Figure 18.10 which also shows standard dimensions. Inlet velocities
should be in the range 100–150 ft/sec, the higher the better, but may be limited by the occurrence of reentrainment and unacceptable pressure drop. The pressure drop is estimated in terms of velocity heads, a value of four being commonly taken. Accordingly,

\[ \Delta P = 4 \rho V^2 / 2g = 4.313 \rho (\text{ft/\text{sec}/100})^2, \text{ psi.} \quad (18.13) \]

For atmospheric air, for instance, this becomes

\[ \Delta P = 0.323(\text{ft/\text{sec}/100})^2, \text{ psi.} \quad (18.14) \]

### EXAMPLE 18.2

**Quantity of Entrainment on the Basis of Sieve Tray Correlations**

The conditions of Example 13.15 will be used. This is the case of a standard sieve tray with 24 in. spacing and to operate at 80% of flooding. The entrainment correlation is Figure 18.4 for which the value of the abscissa was found to be

\[ w_L / w_G \sqrt{p_G / p_L} = 0.2924. \]

At 80% of flooding the ordinate of Figure 18.4 is

\[ \psi = 0.008 \text{ mol entrained liquid/mol liquid downflow.} \]

Since \( w_L / w_G = 259,100 / 271,500 = 0.954 \text{ mol liquid/mol vapor (assuming the same molecular weights)}, \) the entrainment expressed with reference to the vapor flow is

\[ \psi = 0.008(0.954) = 0.0076 \text{ mol liquid/mol vapor flow.} \]

The linear velocity of the vapor was found in Example 13.15 to be 0.597 ft/sec for this condition.
EXAMPLE 18.3
Liquid Knockout Drum (Empty)
Gas at the rate of 3000 cfm and liquid at 25 cfm enter a drum in which entrainment is to be removed. Holdup of liquid in the drum is 10 min. The properties are those of air and water at atmospheric conditions. Find the size of the drum needed to remove droplets greater than 200 μm dia.
Vertical drum, with Eq. (18.9):

\[ u = 0.14 \sqrt{62.4/0.075 - 1} = 4.04 \text{ ft/sec,} \]
\[ D = \sqrt{3000/60(\pi/4)4.04} = 3.97 \text{ ft}, \text{ say 4.0 ft.} \]

From Figure 18.5, the vapor space is a minimum of 5.5 ft. The liquid depth is

\[ L_{eq} = \frac{250}{(\pi/4)D^2} = 19.9 \text{ ft} \quad \text{10 min holdup,} \]
\[ L = 19.9 + 5.5 = 25.4 \text{ ft,} \]
\[ L/D = 25.4/4 = 6.35. \]

Horizontal drum:

The allowable velocity is 25% greater:

\[ u = 1.25(4.04) = 5.05 \text{ ft/sec.} \]

Try several fractional vapor cross sections φ:

\[ D = \sqrt[5]{50/5.05(\pi/4)\phi} = \sqrt[5]{12.61/\phi}, \]
\[ L = 250/(1 - \phi)(\pi/4)D^2 = 25.24\phi/(1 - \phi), \]
\[ h = \text{depth of liquid.} \]

\[ \begin{array}{cccc}
\phi & h/D & D & L/LD \\
0.2 & 0.75 & 7.94 (8.0) & 6.31 (6.2) & 0.78 \\
0.3 & 0.86 & 6.48 (6.5) & 10.82 (10.8) & 1.66 \\
0.4 & 0.96 & 5.61 (6.5) & 16.83 (17.5) & 3.18 \\
0.5 & 1.00 & 5.02 (6.0) & 25.24 (25.5) & 5.10 \\
\end{array} \]

Accordingly, a horizontal vessel between 5.0 and 5.5 ft dia with a liquid depth between 58 and 50% of the diameter falls in the usual economic range.

Achieved by proper design of cyclone separators. For applications such as knockout drums on the suction of compressors, however, it is sufficient to remove droplets greater than 40–50 μm.

Capacity and efficiency depend on the inlet velocity and the dimensions of the vessel. Correlated studies have been made chiefly for the design of Figure 18.9 with a rectangular inlet whose width is D/4 (one-fourth of the vessel diameter) and whose height is 2–3 times the width. A key concept is a critical particle diameter which is the one that is removed to the extent of 50%. The corresponding % removal of other droplet sizes is correlated by Figure 18.11. The equation for the critical particle diameter is

\[ (D_p)_{crit} = \left[ \frac{9\mu D}{4\pi N_s V(\rho - \rho_g)} \right]^{0.5}, \quad (18.15) \]

where D is the diameter of the vessel and V is the inlet linear velocity. The quantity Ns is the number of turns made by the gas in the vessel. A graphical correlation given by Zenz (1982) can be

---

**Figure 18.7.** Key dimensions of knockout drums equipped with mesh pads. (a) Vertical knockout drum. (b) Horizontal knockout drum.
18.6 STORAGE TANKS

Cylindrical tanks for the storage of inflammable liquids above or under ground at near atmospheric pressure are subject to standards of Underwriters Laboratories or of the API. Underwriters covers some smaller sizes. Both sets of standards are restricted to steel construction for essentially noncorrosive service. Various manufacturers supply Underwriter or API tanks as a matter of course.

Standard tanks are made in discrete sizes with some latitude in combinations of diameter and length. For example, Table 18.2 shows the several heights of 30 ft diameter tanks among API standard sizes. The major specification is that of metal wall thickness. In smaller sizes the thickness is determined by requirements of rigidity rather than strength. Some general statements about metal thickness of tanks may be given.

**Horizontal tanks.** Above ground they are limited to 35,000 gal. Normally they are supported on steel structures or concrete saddles at elevations of 6 to 10 ft. The minimum thickness of shell and heads is 3/16 in. in diameters of 48–72 in. and 1/4 in. in diameters of 73–132 in.
**EXAMPLE 18.4**

**Knockout Drum with Wire Mesh Deentrainer**

For the flow conditions of Example 18.2, design a drum with a standard efficiency stainless steel wire mesh pad. For this condition, $k = 0.35$, so that

$$u = 0.35 \sqrt{\frac{62.4}{0.075}} - 1 = 10.09 \text{ ft/sec},$$
$$D = \sqrt{50/\pi/0.75} = 2.51 \text{ ft}.$$

With 2 in. support rings the pad will have a diameter of 34 in. The size of the drum is set largely by the required liquid holdup of 250 cu ft. On the basis of Figure 18.7, the height of vessel above the liquid level is 4 ft. As in Example 18.2, take the diameter to be 4.5 ft. Then

$$L_{eq} = 25[10/(\pi/4)(4.5)]^2 = 15.7 \text{ ft},$$
$$L = 15.7 + 4.0 = 19.7 \text{ ft},$$
$$L/D = 19.7/4.5 = 4.38.$$

This ratio is acceptable. As a check, use Eqs. (18.11) and (18.12):

$$x = \frac{(W_2/W_1)\sqrt{P_e/P_r}}{V_2/V_1} = \frac{V_2}{V_1} \sqrt{P_e/P_r}$$
$$= \frac{25}{3000 \sqrt{62.4/0.075}} = 0.24,$$
$$k = \frac{-0.0073 + 0.263/[0.24^{2.94} + 0.573]}{0.353},$$

which is close to the assumed value, $k = 0.35$.

---

**Figure 18.9.** Typical dimension ratios of a cyclone separator.

**Figure 18.10.** Dimensions of standard liquid knockout drums with tangential inlets.
18.7. MECHANICAL DESIGN OF PROCESS VESSELS

Vertical tanks. Those supported above ground are made with dished or conical bottoms. Flat bottomed tanks rest on firm foundations of oiled sand or concrete. Supported flat bottoms usually are 1/4 in. thick. Roof plates are 3/16 in. thick. Special roof constructions that minimize vaporization losses were mentioned earlier in this chapter; they are illustrated by Mead (1964), by Riegel (1953), and in manufacturers catalogs. The curved sides are made of several courses of plate with thicknesses graduated to meet requirements of strength. The data of the selected API tanks of Table 18.2 include this information. Figure 18.12 illustrates the facilities that normally are provided for a large storage tank.

In order to minimize hazards, storage tanks for inflammable or toxic materials may be buried. Then they are provided with an overburden of 1.3 times the weight of water that the tank could hold in order to prevent floating after heavy rainfalls.

Cylinders with curved heads are used for pressure storage at 5–230 psig. In the range of 5–10 psig, spheroids and other constructions made up with curved surfaces, as in Figure 18.12(c) are being used in quite large sizes, often with refrigeration to maintain sufficiently low pressures. More illustrations of such equipment appear in manufacturers' catalogs and in the books of Mead (1964) and Riegel (1953).

Mention of vessels for the storage of gases was made at the beginning of this chapter, and Figure 18.12(d) shows the principles of some suitable designs. Design for storage of granular solids includes provisions for handling and withdrawal, as in the case of Figure 18.13.

18.7. MECHANICAL DESIGN OF PROCESS VESSELS

Process design of vessels establishes the pressure and temperature ratings, the length and diameter of the shell, the sizes and locations of nozzles and other openings, all internals, and possibly the material of construction and corrosion allowances. This information must be supplemented with many mechanical details before fabrication can proceed, notably wall thicknesses.

Large storage tanks are supported on a concrete pad on the ground. Other vessels are supported off the ground by various means, as in Figure 18.14.

For safety reasons, the design and construction of pressure vessels are subject to legal and insurance standards. The ASME

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**Example 18.5**

**Size and Capacity of Cyclone Separators**

Air at 1000 cuft/sec and density of 0.075 lb/cuft contains particles with density 75 lb/cuft. 50% of the 10 μm diameter particles are to be recovered. Find the sizes and numbers of cyclones needed with inlet velocities in the range of 50–150 ft/sec. The inlet is rectangular with width $D/4$ and height $2.5D/4$, where $D$ is the diameter of the vessel.

Equation (18.15) becomes

$$\frac{D}{N_V} = \frac{4\pi (\rho - \rho_e) D^2}{9 \mu} \left(\frac{10}{304,800}\right)^2 = 0.00876,$$

where $N_V$ is given by Eq. (18.16). The number of vessels in parallel is

$$n = \frac{Q}{AV} = \frac{100}{(2.5/16)D^2V} = \frac{6400}{D^2V}.$$

The results at several velocities are summarized.

<table>
<thead>
<tr>
<th>$V$ (cuft/sec)</th>
<th>$n$</th>
<th>$D$ (ft)</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>3.71</td>
<td>1.62</td>
<td>48.8</td>
</tr>
<tr>
<td>100</td>
<td>5.01</td>
<td>4.39</td>
<td>3.32</td>
</tr>
<tr>
<td>144</td>
<td>5.32</td>
<td>6.71</td>
<td>1.0</td>
</tr>
</tbody>
</table>

From Figure 18.11, the percentage recoveries of other-sized particles are:

$$\frac{D_p}{(D_p)_{crit}} \% \text{Recovered}$$

<table>
<thead>
<tr>
<th>$D_p$</th>
<th>% Recovered</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>9</td>
</tr>
<tr>
<td>0.5</td>
<td>22</td>
</tr>
<tr>
<td>0.6</td>
<td>30</td>
</tr>
<tr>
<td>1</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>70</td>
</tr>
<tr>
<td>6</td>
<td>90</td>
</tr>
<tr>
<td>9</td>
<td>98.5</td>
</tr>
</tbody>
</table>

When the smallest of these cyclones, 1.62 ft dia, is operated at 150 cuft/sec, $N_V = 5.35$, $$(D_p)_{crit} = \left[\frac{9(1.285)(10^{-5})(1.62)}{4\pi (5.35)(150)(75 - 0.075)}\right]^{0.5} = 1.574(10^{-5}) \text{ ft, } 4.80 \mu m.$$
TABLE 18.2. Storage Tanks, Underwriter or API Standard, Selected Sizes

### a. Small Horizontal Underwriter Label

<table>
<thead>
<tr>
<th>Capacity (Gallons)</th>
<th>Diameter</th>
<th>Length</th>
<th>Thickness</th>
<th>Weight (in pounds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>280</td>
<td>42&quot;</td>
<td>4'-0&quot;</td>
<td>1/8&quot;</td>
<td>540</td>
</tr>
<tr>
<td>550</td>
<td>48&quot;</td>
<td>6'-0&quot;</td>
<td>1/8&quot;</td>
<td>800</td>
</tr>
<tr>
<td>1000</td>
<td>48&quot;</td>
<td>10'-8&quot;</td>
<td>1/8&quot;</td>
<td>1,260</td>
</tr>
<tr>
<td>1000</td>
<td>64&quot;</td>
<td>6'-0&quot;</td>
<td>5/32&quot;</td>
<td>1,160</td>
</tr>
<tr>
<td>1500</td>
<td>64&quot;</td>
<td>9'-0&quot;</td>
<td>5/32&quot;</td>
<td>1,550</td>
</tr>
<tr>
<td>2000</td>
<td>64&quot;</td>
<td>12'-0&quot;</td>
<td>5/32&quot;</td>
<td>1,950</td>
</tr>
<tr>
<td>3000</td>
<td>64&quot;</td>
<td>18'-0&quot;</td>
<td>5/32&quot;</td>
<td>2,730</td>
</tr>
<tr>
<td>4000</td>
<td>64&quot;</td>
<td>24'-0&quot;</td>
<td>5/32&quot;</td>
<td>3,510</td>
</tr>
</tbody>
</table>

### b. Horizontal or Vertical with Underwriter Label

<table>
<thead>
<tr>
<th>Nominal Capacity (Gallons)</th>
<th>Diameter</th>
<th>Approx. Length</th>
<th>Thickness</th>
<th>Weight</th>
<th>No. of Supports</th>
</tr>
</thead>
<tbody>
<tr>
<td>5,000</td>
<td>6'-0&quot;</td>
<td>23'-9&quot;</td>
<td>3/8&quot;</td>
<td>5,440</td>
<td>3</td>
</tr>
<tr>
<td>6,000</td>
<td>7'-0&quot;</td>
<td>17'-6&quot;</td>
<td>3/8&quot;</td>
<td>5,130</td>
<td>2</td>
</tr>
<tr>
<td>6,000</td>
<td>8'-0&quot;</td>
<td>16'-1&quot;</td>
<td>3/8&quot;</td>
<td>5,920</td>
<td>2</td>
</tr>
<tr>
<td>6,000</td>
<td>8'-0&quot;</td>
<td>16'-1&quot;</td>
<td>3/8&quot;</td>
<td>6,720</td>
<td>2</td>
</tr>
<tr>
<td>8,000</td>
<td>8'-0&quot;</td>
<td>21'-4&quot;</td>
<td>3/8&quot;</td>
<td>7,280</td>
<td>2</td>
</tr>
<tr>
<td>8,000</td>
<td>8'-0&quot;</td>
<td>21'-4&quot;</td>
<td>3/8&quot;</td>
<td>8,330</td>
<td>2</td>
</tr>
<tr>
<td>10,000</td>
<td>8'-0&quot;</td>
<td>26'-7&quot;</td>
<td>3/8&quot;</td>
<td>8,860</td>
<td>3</td>
</tr>
<tr>
<td>10,000</td>
<td>8'-0&quot;</td>
<td>26'-7&quot;</td>
<td>3/8&quot;</td>
<td>10,510</td>
<td>3</td>
</tr>
<tr>
<td>10,000</td>
<td>10'-0&quot;</td>
<td>17'-2&quot;</td>
<td>3/8&quot;</td>
<td>8,030</td>
<td>2</td>
</tr>
<tr>
<td>10,000</td>
<td>10'-0&quot;</td>
<td>17'-2&quot;</td>
<td>3/8&quot;</td>
<td>9,130</td>
<td>2</td>
</tr>
<tr>
<td>10,000</td>
<td>10'-6&quot;</td>
<td>15'-8&quot;</td>
<td>3/8&quot;</td>
<td>8,160</td>
<td>2</td>
</tr>
<tr>
<td>10,000</td>
<td>10'-6&quot;</td>
<td>15'-8&quot;</td>
<td>3/8&quot;</td>
<td>9,020</td>
<td>2</td>
</tr>
<tr>
<td>15,000</td>
<td>8'-0&quot;</td>
<td>39'-11&quot;</td>
<td>3/8&quot;</td>
<td>13,210</td>
<td>4</td>
</tr>
<tr>
<td>15,000</td>
<td>8'-0&quot;</td>
<td>39'-11&quot;</td>
<td>3/8&quot;</td>
<td>14,620</td>
<td>4</td>
</tr>
<tr>
<td>20,000</td>
<td>10'-0&quot;</td>
<td>34'-1&quot;</td>
<td>3/8&quot;</td>
<td>14,130</td>
<td>3</td>
</tr>
<tr>
<td>20,000</td>
<td>10'-0&quot;</td>
<td>34'-1&quot;</td>
<td>3/8&quot;</td>
<td>16,330</td>
<td>3</td>
</tr>
<tr>
<td>25,000</td>
<td>10'-6&quot;</td>
<td>39'-9&quot;</td>
<td>3/8&quot;</td>
<td>17,040</td>
<td>4</td>
</tr>
<tr>
<td>25,000</td>
<td>10'-6&quot;</td>
<td>39'-9&quot;</td>
<td>3/8&quot;</td>
<td>19,010</td>
<td>4</td>
</tr>
</tbody>
</table>

### c. Large Vertical, API Standard

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Capacity</th>
<th>Shell Plates (Butt Welded)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>Height</td>
<td>42 gal per bbl U.S. Gal</td>
</tr>
<tr>
<td>Ring 1</td>
<td>Ring 2</td>
<td>Ring 3</td>
</tr>
<tr>
<td>Ring 4</td>
<td>Ring 5</td>
<td>Ring 6</td>
</tr>
<tr>
<td>Ring 7</td>
<td>Top Angle</td>
<td>Roof Plates</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21'-0&quot;</td>
<td>18'-0&quot;</td>
<td>1,114</td>
</tr>
<tr>
<td>24'-0&quot;</td>
<td>24'-0&quot;</td>
<td>1,933</td>
</tr>
<tr>
<td>30'-0&quot;</td>
<td>30'-0&quot;</td>
<td>3,024</td>
</tr>
<tr>
<td>30'-0&quot;</td>
<td>39'-111/2</td>
<td>3,769</td>
</tr>
<tr>
<td>30'-0&quot;</td>
<td>35'-101/2</td>
<td>4,510</td>
</tr>
<tr>
<td>37'-101/2</td>
<td>7,075</td>
<td>4,765</td>
</tr>
<tr>
<td>37'-101/2</td>
<td>41'-31/2</td>
<td>5,264</td>
</tr>
<tr>
<td>40'-6&quot;</td>
<td>33'-101/2</td>
<td>7,586</td>
</tr>
<tr>
<td>50'-0&quot;</td>
<td>47'-9&quot;</td>
<td>16,700</td>
</tr>
<tr>
<td>60'-0&quot;</td>
<td>59'-10</td>
<td>20,054</td>
</tr>
<tr>
<td>70'-0&quot;</td>
<td>40'-1&quot;</td>
<td>27,472</td>
</tr>
<tr>
<td>100'-0&quot;</td>
<td>40'-0&quot;</td>
<td>55,960</td>
</tr>
<tr>
<td>150'-0&quot;</td>
<td>48'-0&quot;</td>
<td>151,076</td>
</tr>
</tbody>
</table>
18.7. MECHANICAL DESIGN OF PROCESS VESSELS

Codes apply to vessels greater than 6 in. dia operating above 15 psig. Section VIII Division 1 applies to pressures below 3000 psig and is the one most often applicable to process work. Above 3000 psig some further restrictions are imposed. Division 2 is not pressure limited but has other severe restrictions. Some of the many details covered by Division 1 are indicated by the references to parts of the code on Figure 18.15.

DESIGN PRESSURE AND TEMPERATURE

In order to allow for possible surges in operation, it is customary to raise the maximum operating pressure by 10% or 10–25 psi, whichever is greater. The maximum operating pressure in turn may be taken as 25 psi greater than the normal. The design pressure of vessels operating at 0–10 psig and 600–1000°F is 40 psig. Vacuum systems are designed for 15 psig and full vacuum. Between −20 and 650°F, 50°F is added to the operating temperature, but higher margins of safety may be advisable in critical situations. When subzero temperatures have an adverse effect on the materials of construction, the working temperature is reduced appropriately for safety.

Allowable tensile stresses are one-fourth the ultimate tensile strength of the material of construction. Values at different temperatures are given in Table 18.4 for some steels of which shells and heads are made. Welded joint efficiencies vary from 100% for double-welded butt joints that are fully radiographed to 60% for

Figure 18.12. Examples of equipment for storage of liquids and gases in large quantities. (a) A large tank and its appurtenances, but with no provision for conservation of breathing losses (Graver Tank and Mfg. Co.). (b) Schematic of a covered floating roof tank in which the floating roof rides on the surface of the liquid. They also are made without the fixed roof [R. Martin, Petro/Chem. Eng., 23, (Aug. 1965)]. (c) Cutaway of a 40,000 Bbl spheroid for operation at 10 psig (Chicago Bridge and Iron Co.). (d) Design principles of tanks for storage of gases or liquids subject to breathing losses at atmospheric pressure: water seal, dry seal with flexible curtain, and variable vapor space controlled by a flexible curtain.
Figure 18.13. Equipment for handling, storing and withdrawing of granular solids in a glass manufacturing plant (Stephens-Adamson Mfg. Co.).

single-welded butt joints without backing strips and without radiography. The Code has details.

SHELLS AND HEADS

Although spherical vessels have a limited process application, the majority of pressure vessels are made with cylindrical shells. The heads may be flat if they are suitably buttressed, but preferably they are some curved shape. The more common types of heads are illustrated on Figure 18.16. Formulas for wall thicknesses are in Table 18.3. Other data relating to heads and shells are collected in Table 18.5. Included are the full volume \( V \), and surface \( S \) as well as the volume fraction \( V/V_0 \) corresponding to a fractional depth \( H/D \) in a horizontal vessel. Figure 18.17 graphs this last relationship. For ellipsoidal and dished heads the formulas for \( V/V_0 \) are not exact but are within 2% over the whole range.

FORMULAS FOR STRENGTH CALCULATIONS

The ASME Code provides formulas that relate the wall thickness to the diameter, pressure, allowable stress, and weld efficiency. Since they are theoretically sound only for relatively thin shells, some restrictions are placed on their application. Table 18.3 lists these

Figure 18.14. Methods of supporting vessels. (a) Saddle supports for horizontal vessels, usually of concrete. (b) Bracket or lug supports resting on legs, for either vertical or horizontal vessels. (c) Bracket or lug supports resting on steel structures, for either vertical or horizontal vessels. (d) Straight skirt support for towers and other tall vessels; the bearing plate is bolted to the foundation. (e) Flared skirt for towers and other tall vessels, used when the required number of bolts is such that the bolt spacing becomes less than the desirable 2 ft.
**Table 18.3. Formulas for Design of Vessels under Internal Pressure**

<table>
<thead>
<tr>
<th>Item</th>
<th>Thickness (in.)</th>
<th>Pressure (psi)</th>
<th>Stress (psi)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylindrical shell</td>
<td>PR</td>
<td>SE = 0.6P</td>
<td>P(R + 0.6t)</td>
<td>t ≤ 0.25D, P = 0.385SE</td>
</tr>
<tr>
<td>Flat flanged head (a)</td>
<td>D/0.3P/5</td>
<td>I = 0.9P/0.3D^2</td>
<td>0.3P*P/2^2</td>
<td>r/L = 0.06, L ≤ D + 2t</td>
</tr>
<tr>
<td>Torispherical head (b)</td>
<td>0.885PL</td>
<td>SE = 0.1P</td>
<td>(0.885L + 0.1t)/I</td>
<td></td>
</tr>
<tr>
<td>Torispherical head (b)</td>
<td>PL</td>
<td>2SEt</td>
<td>P(LM + 0.2t)</td>
<td>M = 3 + (L/r)^1/2</td>
</tr>
<tr>
<td>Ellipsoidal head (c)</td>
<td>2SE - 0.2P</td>
<td>2SEt</td>
<td>P(D + 0.2t)</td>
<td>h/D = 4</td>
</tr>
<tr>
<td>Ellipsoidal head (c)</td>
<td>2SE - 0.2P</td>
<td>2SEt</td>
<td>P(D + 0.2t)</td>
<td>K = [2 + (D/2h)^2] / 6, 2 ≤ D/h ≤ 6</td>
</tr>
<tr>
<td>Hemispherical head (d)</td>
<td>2SE - 0.2P</td>
<td>2SEt</td>
<td>P(D + 0.2t)</td>
<td>t ≤ 0.17BD, P ≤ 0.685SE</td>
</tr>
<tr>
<td>Ellipsoidal or shell (e)</td>
<td>2SE - 0.2P</td>
<td>2SEt cos α</td>
<td>(D + 1.2t cos α)</td>
<td>α = 30°</td>
</tr>
</tbody>
</table>

| Torical modal head (e)      | 2(2SE - 0.6P)   | 2SEt cos α     | (D + 1.2t cos α)      | α = 30°                   |

* Nomenclature: D = diameter (in.), E = joint efficiency (0.8–1.0), L = crown radius (in.), P = pressure (psig), h = inside depth of ellipsoidal head (in.), r = knuckle radius (in.), R = radius (in.), S = allowable stress (psi), t = shell or head thickness (in.).

Note: Letters in parentheses in the first column refer to Figure 18.16.
### Table 18.4. Maximum Allowable Tensile Stresses (psi) of Plate Steels

#### (a) Carbon and Low Alloy Steels

<table>
<thead>
<tr>
<th>A.S.M.E. Specification No.</th>
<th>Grade</th>
<th>Nominal composition</th>
<th>Spec. min. nominal tensile strength</th>
<th>For temperatures not exceeding °F.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>-20 to 650</td>
<td>700</td>
</tr>
<tr>
<td><strong>Carbon Steel</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SA515</td>
<td>55</td>
<td>C-Si</td>
<td>55,000</td>
<td>13,700</td>
</tr>
<tr>
<td>SA515</td>
<td>70</td>
<td>C-Si</td>
<td>70,000</td>
<td>17,500</td>
</tr>
<tr>
<td>SA516</td>
<td>55</td>
<td>C-Si</td>
<td>55,000</td>
<td>13,700</td>
</tr>
<tr>
<td>SA516</td>
<td>70</td>
<td>C-Si</td>
<td>70,000</td>
<td>17,500</td>
</tr>
<tr>
<td>SA285</td>
<td>A</td>
<td></td>
<td>45,000</td>
<td>11,200</td>
</tr>
<tr>
<td>SA285</td>
<td>B</td>
<td></td>
<td>50,000</td>
<td>12,500</td>
</tr>
<tr>
<td>SA285</td>
<td>C</td>
<td></td>
<td>55,000</td>
<td>13,700</td>
</tr>
<tr>
<td><strong>Low Alloy Steel</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SA202</td>
<td>A</td>
<td>Cr-Mn-Si</td>
<td>75,000</td>
<td>16,700</td>
</tr>
<tr>
<td>SA202</td>
<td>B</td>
<td>Cr-Mn-Si</td>
<td>85,000</td>
<td>21,200</td>
</tr>
<tr>
<td>SA387</td>
<td>D*</td>
<td>2/3 Cr-1 Mo</td>
<td>60,000</td>
<td>15,000</td>
</tr>
</tbody>
</table>

#### (b) High Alloy Steels

<table>
<thead>
<tr>
<th>A.S.M.E. Specification No.</th>
<th>Grade</th>
<th>Nominal composition</th>
<th>Specified minimum tensile strength</th>
<th>For temperatures not exceeding °F.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>-20 to 100</td>
<td>200</td>
</tr>
<tr>
<td>SA-240</td>
<td>304</td>
<td>18 Cr-8 Ni</td>
<td>75,000</td>
<td>18,700</td>
</tr>
<tr>
<td>SA-240</td>
<td>304L</td>
<td>18 Cr-8 Ni</td>
<td>70,000</td>
<td>15,600</td>
</tr>
<tr>
<td>SA-240</td>
<td>310S</td>
<td>25 Cr-20 Ni</td>
<td>75,000</td>
<td>18,700</td>
</tr>
<tr>
<td>SA-240</td>
<td>316</td>
<td>16 Cr-12 Ni-2 Mo</td>
<td>75,000</td>
<td>18,700</td>
</tr>
<tr>
<td>SA-240</td>
<td>410</td>
<td>13 Cr</td>
<td>65,000</td>
<td>15,500</td>
</tr>
</tbody>
</table>

(ASME Publications).

Relations for cylindrical and spherical shells and for all but the last of the heads of Figure 18.16. For unusual shapes there are no simple methods of design; experience and testing may need to be resorted to if such shapes are required.

The formulas are expressed in terms of inside dimensions.

Although they are rarely needed, formulas in terms of outside dimensions, say $D_o$, may be derived from the given ones by substitution of $D_o - 2t$ for $D$. For the 2:1 ellipsoidal head, for instance,

$$ t = \frac{PD}{2SE - 0.2P} = \frac{P(D_o - 2t)}{2SE - 0.2P} = \frac{PD_o}{2SE + 1.8P} \quad (18.18) $$

Example 18.6 investigates the dimensions and weight of a vessel to meet specifications. It is brought out that pressure vessels with large $L/D$ ratios are lighter and presumably cheaper. A drawback may be the greater ground space needed by the slimmer and longer construction.

In addition to the shell and heads, contributions to the weight of a vessel include nozzles, manways, any needed internals, and supporting structures such as legs for horizontal vessels and skirts for vertical ones. Nozzles and manways are standardized for discrete pressure ratings; their dimensions and weights are listed in manufacturers' catalogs. Accounting for these items may contribute 10-20% to the calculated weight of the vessel.

Mechanical design specification sheets (Appendix B) summarize the information that a fabricator needs in addition to the general specifications of the vessel codes. Not all of the data on the specification summary are necessarily in the province of the process engineer; it may depend on the stage of the design and on who else in the organization is available to do the work.

![Figure 18.16](image-url) Fractional volumes of horizontal cylinders and curved heads at corresponding fractional depths, $H/D$. 
### TABLE 18.5. Heads and Horizontal Cylinders: Formulas for Partially Filled Volumes and Other Data

**Nomenclature**

- \( D \) = diameter of cylinder
- \( H \) = depth of liquid
- \( S \) = surface of head
- \( V_0 \) = volume of full head
- \( \theta \) = angle subtended by liquid level or angle of cone

#### Cylinder

- \( \theta = 2 \arccos(1 - 2H/D) \)
- \( \theta(\text{rad}) = \theta/57.3 \)
- \( V/V_0 = (1/2\pi)(\theta - \sin \theta) \)

#### Hemispherical head

- \( S = 1.571D^2 \)
- \( V = (\pi/3)H^2 (1.5D - H) \)
- \( V/V_0 = 2(H/D)^2(1.5 - H/D) \)

#### Ellipsoidal head \((h = D/4)\)

- \( S = 1.09D^2 \)
- \( V_0 = 0.1309D^3 \)
- \( V/V_0 = 2(H/D)^2(1.5 - H/D) \)

#### Torispherical \((L = D)\)

- \( S = 0.842D^2 \)
- \( V_0 = 0.0778D^3 \)
- \( V/V_0 = 2(H/D)^2(1.5 - H/D) \)

#### Conical

- \( H = (|D - d|/2) \tan \theta \)
- \( = \begin{cases} 0.5(D - d), & \theta = 45^\circ \\ 0.2887(D - d), & \theta = 30^\circ \end{cases} \)
- \( S = 0.785(D + d) \sqrt{D^2 + (D - d)^2}, \text{ curved surface} \)
- \( V = 0.262H(D^2 + Dd + d^2) \)

---

**Figure 18.17.** Types of heads for cylindrical pressure vessels. (a) Flat flanged: KR = knuckle radius, SF = straight flange. (b) Torispherical (dished). (c) Ellipsoidal. (d) Spherical. (e) Conical, without knuckle. (f) Conical, with knuckle. (g) Nonstandard, one of many possible types in use.
EXAMPLE 18.6
Dimensions and Weight of a Horizontal Pressure Drum
A drum is to operate at 500°F and 350 psig and to hold 5000 gal at a depth $H/D = 0.8$. Dished heads are to be used. The material is SA285A. Examine the proportions $L/D = 3$ and 5. Formulas are in Table 18.5:

$$V_{\text{tank}} = \frac{5000}{7.48} = 668.4 \text{ cuft.}$$

Two heads, capacity with $H/D = 0.8$,

$$V_h = \frac{V_o(V/V_o)}{2(0.0778D^3)(2(H/D)^2(1.5 - H/D))] = 0.1394D^3.$$  

Shell capacity with $H/D = 0.8$,

$$\theta = 2 \arccos(1 - 1.6) = 4.4286 \text{ rad,}$$
$$V_s = \frac{V_o(V/V_o)}{(\pi/4)D^2L(1/2\pi)(\theta - \sin \theta)} = 0.6736D^2L$$
$$V_{\text{liquid}} = 668.4 = 0.1394D^3 + 0.6736D^2L$$

with $L/D = 3$,

$$D = \left( \frac{668.4}{2.1601} \right)^{1/3} = 6.76 \text{ ft, say 6.5 ft},$$
$$L = \frac{668.4 - 0.1394D^3}{0.6736D^2} = 22.1 \text{ ft, say 22.0.}$$

Allowable stress $S = 11,200 \text{ psi}.$

Say joint efficiency is $E = 0.9$:

$$t_{\text{shell}} = \frac{PR}{SE - 0.6P} = \frac{350(39)}{0.9(11,200) - 0.6(350)} = 1.38 \text{ in.}$$

Dished head with $L = D$ and $r/L = 0.06$:

$$t_h = \frac{0.885(350)(78)}{0.9(11,200) - 0.1(350)} = 2.41 \text{ in.}$$

Surfaces:
shell, $S = \pi DL = 449.3 \text{ sqft,}$
heads, $S = 2(0.842)D^2 = 71.2 \text{ sqft,}$
Weight = $[(449.3(1.4) + 71.2(2.4))491/12$ $= 32,730 \text{ lbs.}$

The results for $L/D = 3$ and 5 are summarized.

<table>
<thead>
<tr>
<th>Item</th>
<th>$L/D = 3$</th>
<th>$L/D = 5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D$ (ft)</td>
<td>6.5</td>
<td>5.5</td>
</tr>
<tr>
<td>$L$ (ft)</td>
<td>22.0</td>
<td>32.0</td>
</tr>
<tr>
<td>$t_{\text{shell}}$ (in.)</td>
<td>1.38 (1.4)</td>
<td>0.957 (1.0)</td>
</tr>
<tr>
<td>$t_{\text{head}}$ (in.)</td>
<td>2.41 (2.4)</td>
<td>1.67 (1.7)</td>
</tr>
<tr>
<td>Weight (lb)</td>
<td>32,730</td>
<td>26,170</td>
</tr>
</tbody>
</table>

The completed vessel will include the weights of nozzles, a manway and reinforcing around the openings, which may total another 10–20%. The weights of these auxiliaries are stated in manufacturers’ catalogs.
REFERENCES