الجامعة التكنولوجية

قسم الهندسة الكيمياوية

المرحلة الثالثة

تصميم معدات باستخدام الحاسوب

Vessels

Vessels in chemical processing service are of two kinds: substantially

1-Vessels without internals The main functions of this **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.

2- Vessels with internals. The second category comprises the **shells of equipment** such as heat exchangers, reactors, mixers, fractionators, and other equipment whose independently of whatever internals are necessary

1- Drums and Tanks

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**.

1-1 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 For example, reflux drums provide surge between a condenser and its tower and d**. DRUMS P (psig)** Liquid drums usually are **placed horizontal** and gas-liquid separators **vertical**,

The volume of a drum is related to the **flow rate through** it, but it product commonly are horizontal. The **length to diameter ratio** is in depends also on the kinds of controls and on how harmful would the **range 2.5-5.0**, the smaller diameters at higher pressures and for be the consequences of downstream equipment running dry downstream equipment;

1-2 Tanks are larger vessels, of several hours holdup usually. For instance, the feed tank to a batch distillation may hold a day's supply. Their sizes are measured in units of the capacities of connecting transportation equipment:

34,500 gal tank cars, 8000 gal tank trucks, etc.,.

. Common erection practices for liquid storage tanks are:

a. For less than 7000 gal, use vertical tanks mounted on legs.

b. Between 1000 and 10,000 gal, use horizontal tanks mounted on concrete foundation.

c. Beyond lO,OOO 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 sub atmospheric temperatures with external refrigeration or auto refrigeration whereby evolved vapors are compressed, condensed, cooled, and returned to storage.

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, so/ids are stored in bins that are usually of rectangular cross section ***with cone bottoms and hooked up to process with*** conveyors.

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1-2-1 STORAGE TANKS Cylindrical tanks for the storage of inflammable liquids above or under ground at near atmospheric pressure are subject to standards of of the API.

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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 l/4 in. in diameters of 73-132 in.

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 l/4 in. thick. Roof plates are 3/16 in. thick. Special roof constructions that minimize vaporization losses were mentioned

2- CODES AND STANDARDS

The following codes and standards shall be followed unless otherwise specified:
ASME SEC. VIII DIV.1 / For Pressure vessels IS: 2825
ASME SEC. VIII DIV.2 For Pressure vessels (Selectively for high pressure / high thickness / critical service)
ASME SEC. VIII DIV.2 For Storage Spheres
ASME SEC. VIII DIV.3 For Pressure vessels (Selectively for high pressure)
API 650 / IS: 803 For Storage Tanks.
API 620 For Low Pressure Storage Tanks

3- 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.

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

The materials that are used in pressure vessel construction are:

1. _ Steels (carbon steel ,stainless steel etc)
2. _ Nonferrous materials such as aluminum and copper
3. _ Specialty metals such as titanium and zirconium
4. _ Nonmetallic materials, such as, plastic, composites and concrete
5. _ Metallic and nonmetallic protective coatings

The mechanical properties that generally are of interest are:

1. _ Yield strength
2. _ Ultimate strength
3. _ Reduction of area (a measure of ductility)
4. _ Fracture toughness
5. _ Resistance to corrosion

Mechanical loads on the pressure vessel include those due to:

1. _ Pressure
2. _ Dead weight
3. _ Piping
4. wind loadings should be considered

4- DESIGN CRITERIA

Equipment shall be designed in compliance with the latest design code requirements, and applicable standards/ Specifications.

4-1 Pressure

Pressure for each vessel shall be specified in the following manner:

Operating Pressure Maximum pressure likely to occur any time during the lifetime of the vessel

Design Pressure

a) When operating pressure is up to 70 Kg./cm2 g , Design pressure shall be equal to operating pressure plus 10% (minimum 1Kg./cm2 g).

b) When operating pressure is over 70 Kg./cm2 g , Design pressure shall be equal to operating pressure plus 5% (minimum 7 Kg./cm2g).
c) Vessels operating under vacuum / partial vacuum shall be designed for an external pressure of 1.055 Kg./cm2 g.
d) Vessels shall be designed for steam out conditions if specified on process data sheet

Test Pressure

a) Pressure Vessels shall be hydrostatically tested in the fabricators shop to 1.5 /1.3/ 1.25 (depending on design code) times the design pressure corrected for temperature.

b) In addition, all vertical vessels / columns shall be designed so as to permit site testing of the vessel at a pressure of 1.5/ 1.3 / 1.25 (depending on design code) times the design pressure measured at the top with the vessel in the vertical position and completely filled with water. The design shall be based on fully corroded condition.

c) Vessels open to atmosphere shall be tested by filling with water to the top.

4-2 Temperature

Temperature for each vessel shall be specified in the following manner:

Operating Temperature Maximum / minimum temperature likely to occur any during the lifetime of vessel.

Design temperature

a) For vessels operating at 0C and over:

Design temperature shall be equal to maximum operating temperature plus 15 0C.

b) For Vessels operating below 0C:

Design temperature shall be equal to lowest operating temperature.

c) Minimum Design Metal Temperature (MDMT) shall be lower of minimum atmospheric temperature and minimum operating temperature.

4-3 Wind Consideration

Wind load shall be calculated on the basis of IS : 875 / site data.

a) Drag coefficient for cylindrical vessels shall be 0.7 minimum.

b) Drag coefficient for spherical vessel shall be 0.6 minimum.

4-4 Earthquake Consideration :

Earthquake load shall be calculated in accordance with IS : 1893 / site data if specially developed and available

4-5 Maximum Allowable Stress (Nominal Design Strength)

For design purposes, it is necessary to decide a value for the maximum allowable stress (nominal design strength) that can be accepted in the material of construction.

This is determined by applying a suitable safety factor to the maximum stress that the material could be expected to withstand without failure under standard test conditions. The safety factor allows for any uncertainty in the design methods, the loading, the quality of the materials, and the workmanship

Major Loads

1. Design pressure: including any significant static head of liquid.
2. Maximum weight of the vessel and contents, under operating conditions.
3. Maximum weight of the vessel and contents under the hydraulic test conditions.
4. Wind loads.
5. Earthquake (seismic) loads.
6. Loads supported by, or reacting on, the vessel.

Subsidiary Loads

1. Local stresses caused by supports, internal structures, and connecting pipes.
2. Shock loads caused by water hammer or by surging of the vessel contents.
3. Bending moments caused by eccentricity of the center of the working pressure relative to the neutral axis of the vessel.
4. Stresses due to temperature differences and differences in the coefficient of expansion of materials.
5. Loads caused by fluctuations in temperature and pressure.

4-6 Welded-Joint Efficiency and Construction Categories

The strength of a welded joint will depend on the type of joint and the quality of the welding. The ASME BPV Code Sec. VIII D.1 defines four categories of weld (Part UW-3):

A Longitudinal or spiral welds in the main shell, necks or nozzles, or circumferential welds connecting hemispherical heads to the main shell, necks, or nozzles;

B Circumferential welds in the main shell, necks, or nozzles or connecting a formed head other than hemispherical;

C Welds connecting flanges, tube sheets, or flat heads to the main shell, a formed head, neck, or nozzle;

The soundness of welds is checked by visual inspection and by nondestructive testing (radiography).

4-7 Corrosion allowance :

Unless otherwise specified by Process Licensor, minimum corrosion allowance shall be considered as follows :

- Carbon Steel, low alloy steel column, Vessels, Spheres : 1.5 mm
- Clad / Lined vessel: Nil
- Storage Tank, shell and bottom : 1.5 mm
- Storage tank, Fixed roof / Floating Roof : Nil

For alloy lined or clad vessels, no corrosion allowance is required on the base metal. The cladding or lining material (in no case less than 1.5 mm thickness) shall be considered for corrosion allowance.

Cladding or lining thickness shall not be included in strength calculations.

Corrosion allowance for flange faces of Girth / Body flanges shall be considered equal to that specified for vessel

4-8 Tank Capacity

Capacity shall be specified as Nominal capacity and stored capacity

Nominal capacity for fixed roof tanks be volume of cylindrical shell.

Nominal capacity for floating roof tanks shall be volume of cylindrical shell minus free board volume.

Stored capacity shall be 90% of Nominal capacity.

Sphere :-Stored capacity shall be 85% of nominal capacity.

4-9 Manholes :

a) Vessels and columns with diameter between 900 and 1000 mm shall be provided with 450 NB manhole. Vessels and columns with diameter greater than 1000mm shall be provided with 500 NB manhole. However, if required vessels and columns with diameter 1200mm and above may be provided with 600NB manhole.

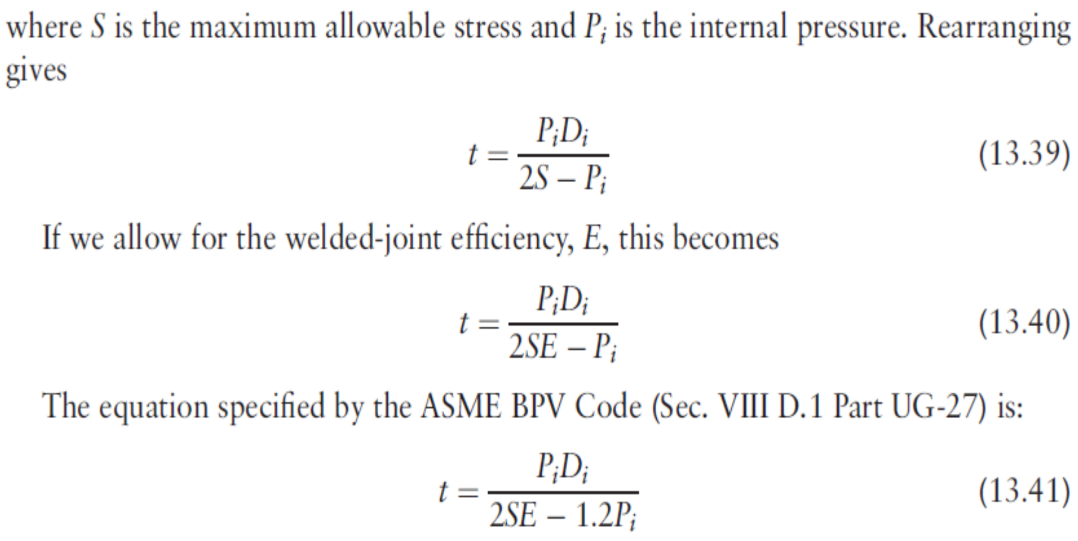
5- THE DESIGN OF THIN-WALLED VESSELS UNDER INTERNAL PRESSURE

5-1 Cylinders and spherical shell

Cylinders and Spherical Shells

For a cylindrical shell, the minimum thickness required to resist internal pressure can be determined from equations below .

If DI is internal diameter and t the minimum thickness required, the mean diameter will be (Di t); substituting this for D in equation gives



where S is the maximum allowable stress and P_i is the internal pressure. Rearranging gives

$$t = \frac{P_i D_i}{2S - P_i} \tag{13.39}$$

If we allow for the welded-joint efficiency, E, this becomes

$$t = \frac{P_i D_i}{2SE - P_i} \tag{13.40}$$

The equation specified by the ASME BPV Code (Sec. VIII D.1 Part UG-27) is:

$$t = \frac{P_i D_i}{2SE - 1.2P_i} \tag{13.41}$$

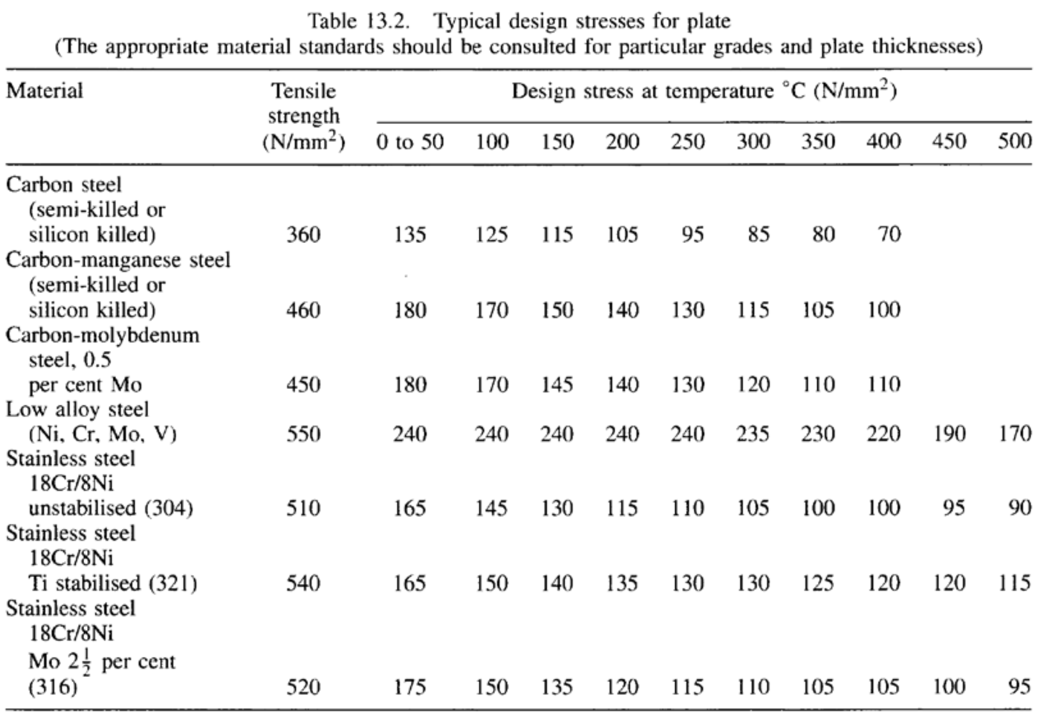
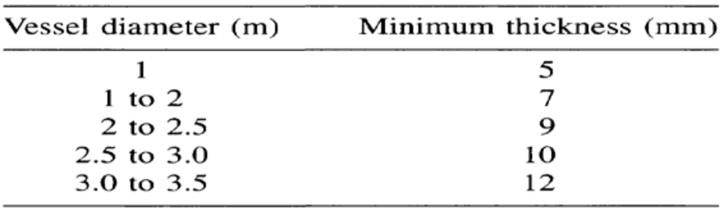


Table 13.2. Typical design stresses for plate
(The appropriate material standards should be consulted for particular grades and plate thicknesses)

Material	Tensile strength (N/mm^2)	Design stress at temperature °C (N/mm^2)									
		0 to 50	100	150	200	250	300	350	400	450	500
Carbon steel (semi-killed or silicon killed)	360	135	125	115	105	95	85	80	70		
Carbon-manganese steel (semi-killed or silicon killed)	460	180	170	150	140	130	115	105	100		
Carbon-molybdenum steel, 0.5 per cent Mo	450	180	170	145	140	130	120	110	110		
Low alloy steel (Ni, Cr, Mo, V)	550	240	240	240	240	240	235	230	220	190	170
Stainless steel 18Cr/8Ni unstabilised (304)	510	165	145	130	115	110	105	100	100	95	90
Stainless steel 18Cr/8Ni Ti stabilised (321)	540	165	150	140	135	130	130	125	120	120	115
Stainless steel 18Cr/8Ni Mo $2\frac{1}{2}$ per cent (316)	520	175	150	135	120	115	110	105	105	100	95

5-1-1 Minimum practical wall thickness

There will be a minimum wall thickness required to ensure that any vessel is sufficiently rigid to withstand its own weight, and any incidental loads. As a general guide the wall thickness of any vessel should not be less than the values given below; the values include a corrosion allowance of 2 mm:



Vessel diameter (m)	Minimum thickness (mm)
1	5
1 to 2	7
2 to 2.5	9
2.5 to 3.0	10
3.0 to 3.5	12

5-2 . Heads and closures

The ends of a cylindrical vessel are closed by heads of various shapes. The principal types used are:

1. Flat plates and formed flat heads;
2. Hemispherical heads;
3. Ellipsoidal heads;.
4. Torispherical heads;.

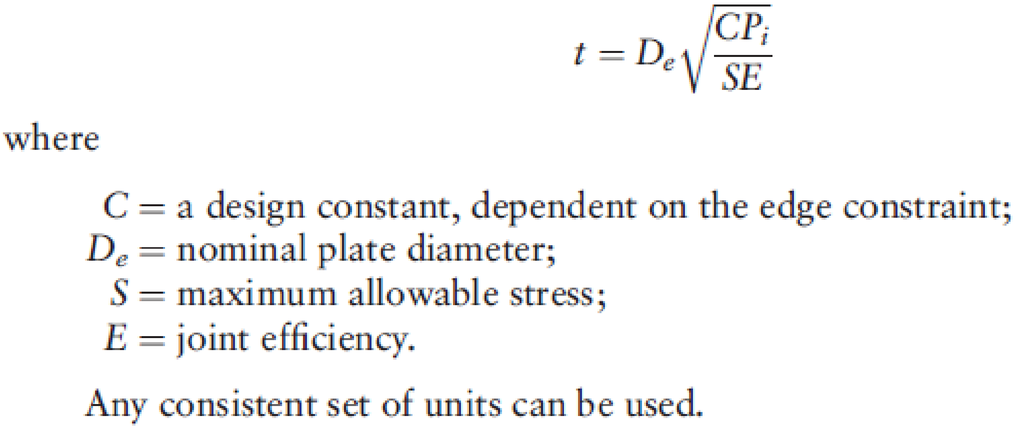
5-2-1 Design of Flat Ends

Though the fabrication cost is low, flat ends are not a structurally efficient form, and very thick plates would be required for high pressures or large diameters.

The design equations used to determine the thickness of flat ends are based on the analysis of stresses in flat plates;.

The thickness required will depend on the degree of constraint at the plate periphery.

The ASME BPV Code specifies the minimum thickness as



$$t = D_e\sqrt{\frac{CP_i}{SE}}$$

where

C = a design constant, dependent on the edge constraint;
D_e = nominal plate diameter;
S = maximum allowable stress;
E = joint efficiency.

Any consistent set of units can be used.

5-2-2 Design of Domed Ends

Design equations and charts for the various types of domed heads are given in the ASME BPV Code and should be used for detailed design.

A hemispherical head is the strongest shape; capable of resisting about twice the pressure of **a torispherical head** of the same thickness. The cost of forming **a hemispherical head** will, however, be higher than that for a shallow **torispherical head**. **Hemispherical heads** are used for high pressures.

Hemispherical Heads

It can be seen by examination of equations that for equal stress in the cylindrical section and hemispherical head of a vessel, the thickness of the head need only be half that of the cylinder. However, as the dilation of the two parts would then be different, discontinuity stresses would be set up at the head and cylinder junction

$$t = \frac{P_i D_i}{4SE - 0.4P_i}$$

Ellipsoidal Heads

Most standard ellipsoidal heads are manufactured with a major and minor axis ratio of 2:1. For this ratio, the following equation can be used to calculate the minimum thickness required (ASME BPV Code Sec. VIII D.1 Part UG-3

$$t = \frac{P_i D_i}{2SE - 0.2P_i}$$

Torispherical Heads

There are two junctions in a torispherical end closure: that between the cylindrical section and the head, and that at the junction of the crown and the knuckle radii. The bending and shear stresses caused by the differential dilation that will occur at these points must be taken into account in the design of the heads. The ASME BPV Code gives the design equation (Sec. VIII D.1 Part UG-32):

$$t = \frac{0.885 P_i R_c}{SE - 0.1 P_i}$$

where R_c = crown radius.

Standard torispherical heads (dished ends) are the most commonly used end closure for vessels up to operating pressures of 15 bar. ellipsoidal head. above 15 bar will usually prove to be the most economical closure to use.

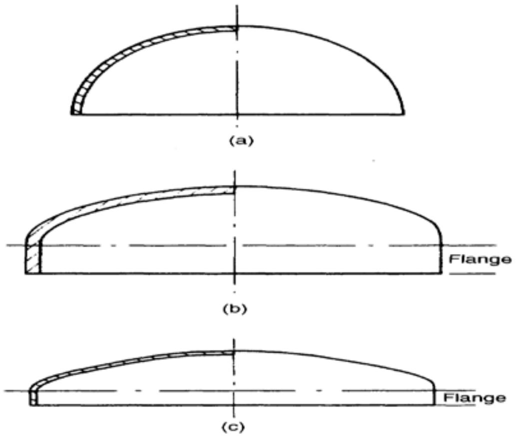
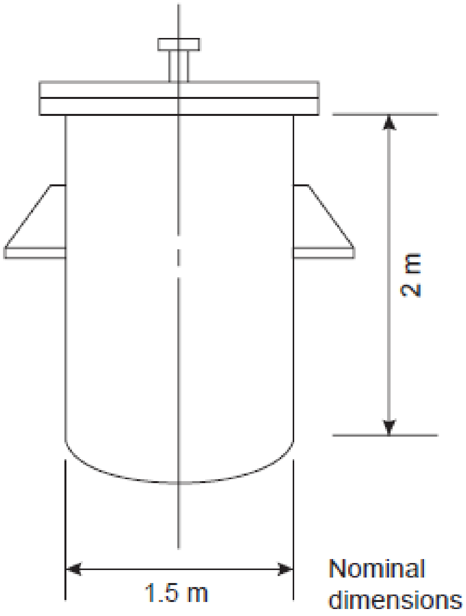


Figure 13.10. Domed heads (*a*) Hemispherical (*b*) Ellipsoidal (*c*) Torispherical

Example 13.1

Estimate the thickness required for the component parts of the vessel shown in the diagram. The vessel is to operate at a pressure of 14 bar (absolute) and temperature of 300 C. The material of construction will be plain carbon steel. Welds will be fully radiographed. A corrosion allowance of 2 mm should be used. **And prepare a data sheet for the equipment**



Solution

Design pressure, taken as 10% above operating gage pressure,

$$
\begin{aligned}
&= (14 - 1) \times 1.1 \\
&= 14.3 \text{ bar} \\
&= 1.43 \text{ N/mm}^2
\end{aligned}
$$

Design temperature 260°C (500°F).
From Table 13.2, maximum allowable stress $= 12.9 \times 10^3$ psi $= 88.9 \text{ N/mm}^2$.

Cylindrical Section

$$t = \frac{1.43 \times 1.5 \times 10^3}{(2 \times 89 \times 1) - (1.2 \times 1.43)} = 12.2\,\text{mm}$$

$$\text{add corrosion allowance} \quad 12.2 + 2 = 14.2\,\text{mm} \tag{13.41}$$

$$\text{say} \quad \underline{\underline{15\text{ mm plate}}} \quad \text{or} \quad \underline{\underline{9/16\text{ inch plate}}}$$

Domed Head

Try a standard dished head (torisphere):

crown radius $R_c = D_i = 1.5$ m
knuckle radius $= 6\%\ R_c = 0.09$ m

A head of this size would be formed by pressing: no joints, so $E = 1$.

$$t = \frac{0.885 \times 1.43 \times 1.5 \times 10^3}{(89 \times 1) - (0.1 \times 1.43)} = \underline{\underline{21.4\,\text{mm}}} \tag{13.46}$$

Try a "standard" ellipsoidal head, ratio major: minor axes = 2:1

$$t = \frac{1.43 \times 1.5 \times 10^3}{(2 \times 89 \times 1) - (0.2 \times 1.43)} = \underline{\underline{12.1\,\text{mm}}} \tag{13.45}$$

So, an ellipsoidal head would probably be the most economical. Take as the same thickness as the wall, 15 mm or 9/16 inch.

Flat Head

Use a full-face gasket $C = 0.25$
D_e = bolt circle diameter, take as approximately 1.7 m.

$$t = 1.7 \times 10^3 \sqrt{\frac{0.25 \times 1.43}{89 \times 1}} = \underline{\underline{107.7\,\text{mm}}} \tag{13.44}$$

Add corrosion allowance and round off to $\underline{\underline{111\text{ mm}}}$ ($4\,^3/_8$ inch).

This shows the inefficiency of a flat cover. It would be better to use a flanged domed head.

GAS-LIQUID SEPARATORS

The separation of liquid droplets and mists from gas or vapour streams is analogous to the separation of solid particles and, with the possible exception of filtration, the same techniques and equipment can be used. Where the carryover of some fine droplets can be tolerated it is often sufficient to rely on gravity settling in a vertical or horizontal separating vessel (knockout pot).

Settling velocity

Equation below can be used to estimate the settling velocity of the liquid droplets, for the design of separating vessels.

$$u_t = 0.07[(\rho_L - \rho_v)/\rho_v)]^{1/2}$$

where *ut* = settling velocity, nVs,
pi — liquid density, kg/m3,
pv — vapour density, kg/m3.
If a demister pad is not used, the value of *ut* obtained from equation should be multiplied by a factor of 0.15 to provide a margin of safety and to allow for flow surges.

Vertical separators

The layout and typical proportions of a vertical liquid-gas separator are shown in Figure 10.5 la.
The diameter of the vessel must be large enough to slow the gas down to below the velocity at which the particles will settle out. So the minimum allowable diameter will Figure 10.5 la. Vertical liquid-vapour Separator
be given by:

$$D_v = \sqrt{\left(\frac{4V_v}{\pi u_s}\right)} \tag{10.11}$$

where D_v = minimum vessel diameter, m,
V_v = gas, or vapour volumetric flow-rate, m^3/s,
$u_s = u_t$, if a demister pad is used, and 0.15 u_t for a separator without a demister pad; u_t from equation (10.10), m/s.

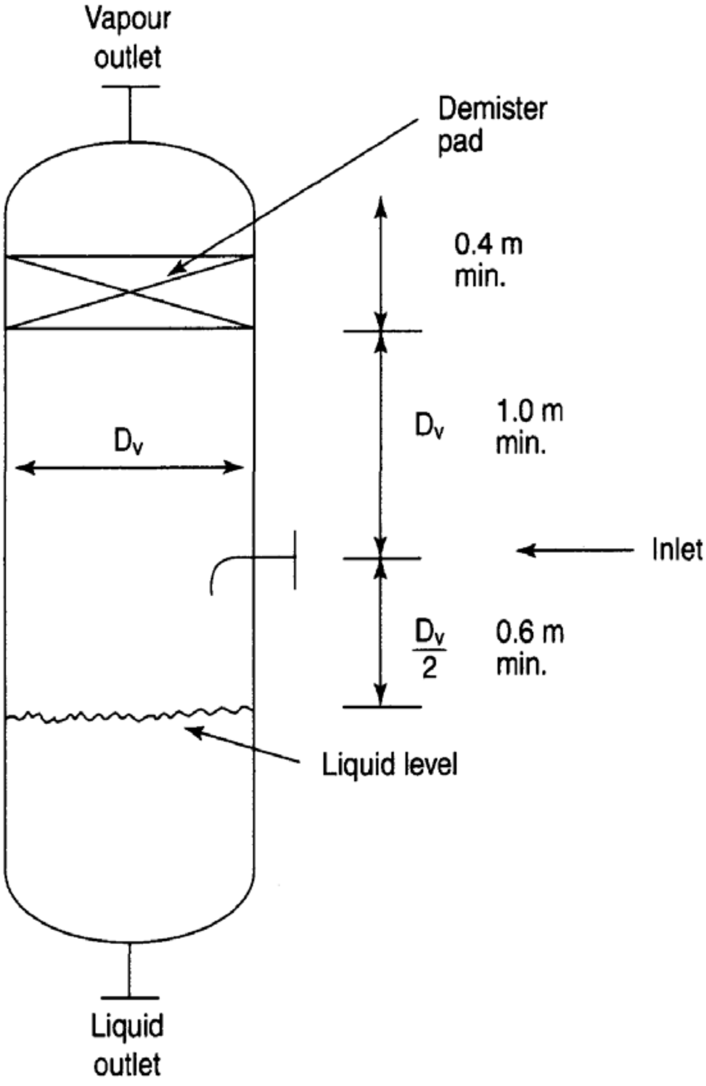


Figure 10.51*a*. Vertical liquid-vapour Separator

The height of the vessel outlet above the gas inlet should be sufficient to allow for disengagement of the liquid drops. A height equal to the diameter of the vessel or 1 m, which ever is the greatest, should be used, see Figure . The liquid level will depend on the hold-up time necessary for smooth operation and control; typically 10 minutes would be allowed.

Example 10.5

Make a preliminary design for a separator to separate a mixture of steam and water; flow-rates: steam 2000 kg/h, water 1000 kg/h; operating pressure 4 bar. **And prepare a data sheet for the equipment**

Solution

From steam tables,' at 4 bar: saturation temperature 143.6°C, liquid density 926.4 kg/m3, vapour density 2.16 kg/m3.

$$u_t = 0.07[(926.4 - 2.16)/2.16]^{\frac{1}{2}} = 1.45 \text{ m/s}$$

As the separation of condensate from steam is unlikely to be critical, a demister pad will not be specified.

So, *ut* = 0.15 x 1.45 = 0.218 m/s

$$\text{Vapour volumetric flow-rate} = \frac{2000}{3600 \times 2.16} = 0.257 \text{ m}^3/\text{s}$$

$$D_v = \sqrt{[(4 \times 0.257)/(\pi \times 0.218)]} = 1.23 \text{ m, round to } 1.25 \text{ m (4 ft).} \qquad (10.11)$$

$$\text{Liquid volumetric flow-rate} = \frac{1000}{3600 \times 926.14} = 3.0 \times 10^{-4} \text{ m}^3/\text{s}$$

Allow a minimum of 10 minutes hold-up.

$$\text{Volume held in vessel} = 3.0 \times 10^{-4} \times (10 \times 60) = 0.18 \text{ m}^3$$

$$\text{Liquid depth required, } h_v = \frac{\text{volume held-up}}{\text{vessel cross-sectional area}}$$

$$= \frac{0.18}{(\pi \times 1.25^2/4)} = 0.15 \text{ m}$$

Increase to 0.3 m to allow space for positioning the level controller.

Operating Pressure, bar	Length: Diameter, L_v/D_v
0–20	3
20–35	4
>35	5

The layout of a typical horizontal separator is shown in Figure 10.51*b*.

A horizontal separator would be selected when a long liquid hold-up time is required.

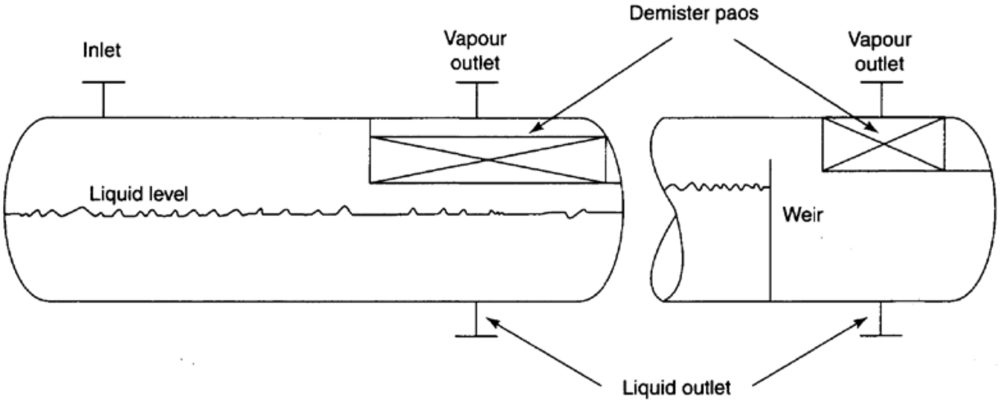


Figure 10.51*b*. Horizontal liquid vapour Separator

In the design of a horizontal separator the vessel diameter cannot be determined independently of its length, unlike for a vertical separator. The diameter and length, and the liquid level, must be chosen to give sufficient vapour residence time for the liquid droplets to settle out, and for the required liquid hold-up time to be met.

The most economical length to diameter ratio will depend on the operating pressure (see Chapter 13). As a general guide the following values can be used:

Operating pressure, bar	Length: diameter, L_v/D_v
0–20	3
20–35	4
>35	5

The relationship between the area for vapour flow, A_v, and the height above the liquid level, h_v, can been found from tables giving the dimensions of the segments of circles; see Perry and Green (1984), or from Figure 11.32 and 11.33 in Chapter 11.

For preliminary designs, set the liquid height at half the vessel diameter,

$$h_v = D_v/2 \text{ and } f_v = 0.5,$$

where f_v is the fraction of the total cross-sectional area occupied by the vapour.

The design procedure for horizontal separators is illustrated in the following example, example 10.6.

Example 10.6

Design a horizontal separator to separate 10,000 kg/h of liquid, density 962.0 kg/m^3, from 12,500 kg/h of vapour, density 23.6 kg/m^3. The vessel operating pressure will be 21 bar.

Solution

$$u_t = 0.07[(962.0 - 23.6)/23.6]^{1/2} = 0.44 \text{ m/s}$$

Try a separator without a demister pad.

$$u_a = 0.15 \times 0.44 = 0.066 \text{ m/s}$$

$$\text{Vapour volumetric flow-rate} = \frac{12{,}500}{3600 \times 23.6} = 0.147 \text{ m}^3/\text{s}$$

Take $h_v = 0.5D_v$ and $L_v/D_v = 4$

$$\text{Cross-sectional area for vapour flow} = \frac{\pi D_v^2}{4} \times 0.5 = 0.393Dv^2$$

$$\text{Vapour velocity, } u_v = \frac{0.147}{0.393Dv^2} = 0.374D_v^{-2}$$

Vapour residence time required for the droplets to settle to liquid surface

$$= h_v/u_a = 0.5D_v/0.66 = 7.58D_v$$

Actual residence time = vessel length/vapour velocity

$$= L_v/u_v = \frac{4D_v}{0.374 \text{ Dv}^{-2}} = 10.70D_v^3$$

For satisfactory separation required residence time = actual.

So, $7.58D_v = 10.70D_v^3$

$D_v = 0.84$ m, say 0.92 m (3 ft, standard pipe size)

Liquid hold-up time,

$$\text{liquid volumetric flow-rate} = \frac{10{,}000}{3600 \times 962.0} = 0.00289 \text{ m}^3/\text{s}$$

$$\text{liquid cross-sectional area} = \frac{\pi \times 0.92^2}{4} \times 0.5 = 0.332 \text{ m}^2$$

Length, $L_v = 4 \times 0.92 = 3.7$ m

Hold-up volume $= 0.332 \times 3.7 = 1.23$ m^3

Hold-up time = liquid volume/liquid flow-rate

$= 1.23/0.00289 = 426$ s = 7 minutes.

This is unsatisfactory, 10 minutes minimum required.

Need to increase the liquid volume. This is best done by increasing the vessel diameter. If the liquid height is kept at half the vessel diameter, the diameter must be increased by a factor of roughly $(10/7)^{0.5} = 1.2$.

New $D_v = 0.92 \times 1.2 = 1.1$ m

Check liquid residence time,

$$\text{new liquid volume} = \frac{\pi \times 1.1^2}{4} \times 0.5 \times (4 \times 1.1) = 2.09\ \text{m}^3$$

$$\text{new residence time} = 2.09/0.00289 = 723\ \text{s} = 12\ \text{minutes, satisfactory}$$

LIQUID-LIQUID SEPARATION

Separation of two liquid phases, immiscible or partially miscible liquids, is a common requirement in the process industries.

Decanters (settlers)

Decanters are used to separate liquids where there is a sufficient difference in density between the liquids for the droplets to settle readily. Decanters are essentially tanks which give sufficient residence time for the droplets of the dispersed phase to rise (or settle) to the interface between the phases and coalesce. In an operating decanter there will be three distinct zones or bands: clear heavy liquid; separating dispersed liquid (the dispersion zone); and clear light liquid

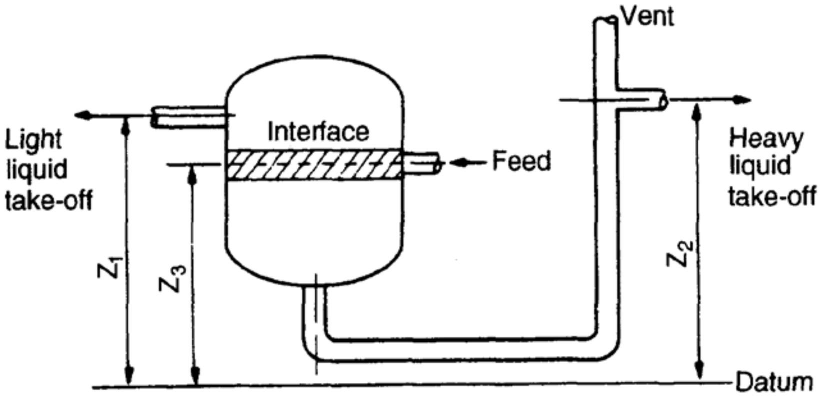


Figure 10.38. Vertical decanter

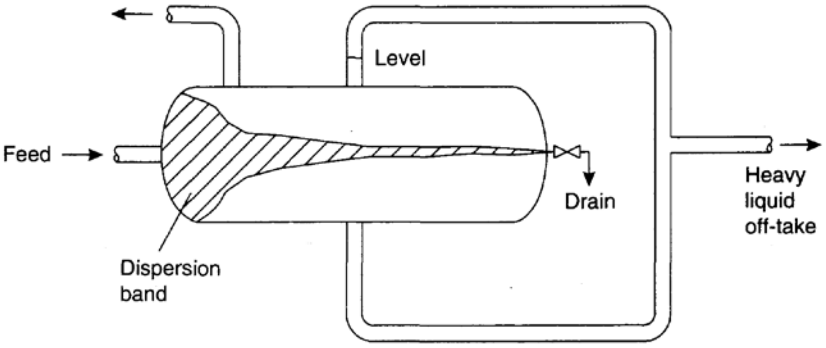


Figure 10.39. Horizontal decanter

The height of the take-off can be determined by making a pressure balance. Neglecting friction loss in the pipes, the pressure exerted by the combined height of the heavy and light liquid in the vessel must be balanced by the height of the heavy liquid in the take-off leg, Figure 10.38.

$$(z_1 - z_3)\rho_1 g + z_3 \rho_2 g = z_2 \rho_2 g$$

hence

$$z_2 = \frac{(z_1 - z_3)\rho_1}{\rho_2} + z_3 \tag{10.5}$$

where ρ_1 = density of the light liquid, kg/m^3,
ρ_2 = density of the heavy liquid, kg/m^3,
z_1 = height from datum to light liquid overflow, m,
z_2 = height from datum to heavy liquid overflow, m,
z_3 = height from datum to the interface, m.

Decanter design

A rough estimate of the decanter volume required can be made by taking **a hold-up time of 5 to 10 min,** which is usually sufficient where emulsions are not likely to form.

The decanter vessel is sized on the basis that the **velocity of the continuous phase must be less than settling velocity of the droplets of the dispersed phase.** Plug flow is assumed, and the velocity of the continuous phase calculated using the area of the interface:

The height of the liquid interface should be measured accurately when the liquid densities are close, when one component is present only in small quantities, or when the throughput is very small. A typical scheme for the automatic control of the interface, using a level instrument that can detect the position of the interface, is shown in Figure . Where one phase is present only in small amounts, it is often recycled to the decanter feed to give more stable operation.

Decanter Design

A rough estimate of the decanter volume required can be made by taking a holdup time of 5 to 10 minutes, which is usually sufficient where emulsions are not likely to form. Methods for the design of decanters are given by Hooper (1997) and Signales (1975). The general approach taken is outlined here and illustrated by Example 10.3.

The decanter vessel is sized on the basis that the velocity of the continuous phase must be less than settling velocity of the droplets of the dispersed phase. Plug flow is assumed and the velocity of the continuous phase calculated using the area of the interface:

$$u_c = \frac{L_c}{A_i} < u_d$$

where

u_d = settling velocity of the dispersed phase droplets, m/s;
u_c = velocity of the continuous phase, m/s;

L_c = continuous phase volumetric flow rate, m^3/s;
A_i = area of the interface, m^2.

Stokes' law is used to determine the settling velocity of the droplets:

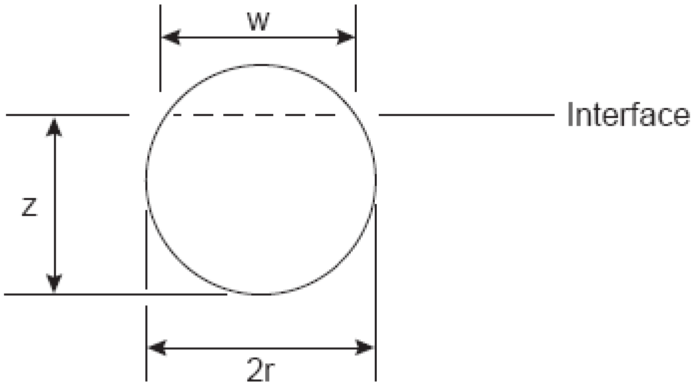
$$u_d = \frac{d_d^2 g(\rho_d - \rho_c)}{18\mu_c} \tag{10.7}$$

where

d_d = droplet diameter, m;
u_d = settling (terminal) velocity of the dispersed phase droplets with diameter d, m/s;
ρ_c = density of the continuous phase, kg/m^3;
ρ_d = density of the dispersed phase, kg/m^3;
μ_c = viscosity of the continuous phase, $N\ s/m^2$;
g = gravitational acceleration, $9.81\ m/s^2$.

of 150 mm, which is well below the droplet sizes normally found in decanter feeds. If the calculated settling velocity is greater than 4_10_3 m/s, then a figure of 4_ 10_3 m/s is used.

For a horizontal, cylindrical, decanter vessel, the interfacial area will depend on the position of the interface.



$A_i = wl$

$$w = 2(2rs - z^2)^{1/2}$$

where

w = width of the interface, m;
z = height of the interface from the base of the vessel, m;
l = length of the cylinder, m;
r = radius of the cylinder, m.

For a vertical, cylindrical decanter:

$$A_i = \pi r^2$$

Example 10.3

Design a decanter to separate a light oil from water.
The oil is the dispersed phase.
Oil, flow rate 1000 kg/h, density 900 kg/m3, viscosity 3mN s/m2.
Water, flow rate 5000 kg/h, density 1000 kg/m3, viscosity 1mN s/m2.

And prepare a data sheet for the equipment

Solution

Take $d_d = 150\ \mu\text{m}$

$$
\begin{aligned}
u_d &= \frac{(150 \times 10^{-6})^2 9.81(900 - 1000)}{18 \times 1 \times 10^{-3}} \\
&= -0.0012\ \text{m/s},\ -1.2\ \text{mm/s (rising)}
\end{aligned}
$$

As the flow rate is small, use a vertical, cylindrical vessel.

$$
L_c = \frac{5000}{1000} \times \frac{1}{3600} = 1.39 \times 10^{-3}\ \text{m}^3/\text{s}
$$

$$
u_c \not> u_d, \text{ and } u_c = \frac{L_c}{A_i}
$$

hence

$$
\begin{aligned}
A_i &= \frac{1.39 \times 10^{-3}}{0.0012} = 1.16\ \text{m}^2 \\
r &= \sqrt{\frac{1.16}{\pi}} = 0.61\ \text{m} \\
\text{diameter} &= \underline{\underline{1.2\ \text{m}}}
\end{aligned}
$$

Take the height as twice the diameter, a reasonable value for a cylinder:

$$
\text{height} = \underline{\underline{2.4\ \text{m}}}
$$

Take the dispersion band as 10% of the height = $\underline{\underline{0.24\ \text{m}}}$.

Check the residence time of the droplets in the dispersion band:

$$\frac{0.24}{u_d} = \frac{0.24}{0.0012} = 200\,\text{s}\ (\sim 3\ \text{min})$$

This is satisfactory; a time of 2 to 5 minutes is normally recommended for control purposes. Check the size of the water (continuous, heavy phase) droplets that could be entrained with the oil (light phase).

$$\begin{aligned}\text{Velocity of oil phase} &= \frac{1000}{900} \times \frac{1}{3600} \times \frac{1}{1.16}\\ &= 2.7 \times 10^{-4}\ \text{m/s}\ (0.27\,\text{mm/s})\end{aligned}$$

From equation 10.7

$$d_d = \left[\frac{u_d 18 \mu_c}{g(\rho_d - 2\rho_c)}\right]^{1/2}$$

so the entrained droplet size will be

$$\begin{aligned}&= \left[\frac{2.7 \times 10^{-4} \times 18 \times 3 \times 10^{-3}}{9.81(1000 - 900)}\right]^{1/2}.\\ &= 1.2 \times 10^{-4}\text{m} = 120\,\mu\text{m}\end{aligned}$$

which is satisfactory; below 150 μm.

Piping Arrangement

To minimize entrainment by the jet of liquid entering the vessel, the inlet velocity for a decanter should keep below 1 m/s.

$$\text{Flow-rate} = \left[\frac{1000}{900} + \frac{5000}{1000}\right]\frac{1}{3600} = 1.7 \times 10^{-3}\ \text{m}^3/\text{s}$$

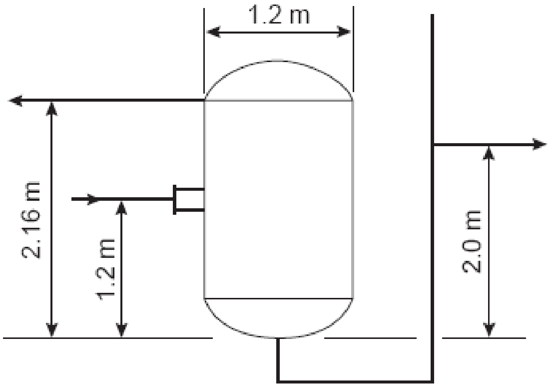
$$\text{Area of pipe} = \frac{1.7 \times 10^{-3}}{1} = 1.7 \times 10^{-3}\text{m}^2$$

$$\text{Pipe diameter} = \sqrt{\frac{1.7 \times 10^{-3} \times 4}{\pi}} = 0.047\,\text{m, say } \underline{\underline{50\ \text{mm}}}$$

Take the position of the interface as halfway up the vessel and the light liquid takeoff as at 90% of the vessel height, then

$$\begin{aligned}z_1 &= 0.9 \times 2.4 = 2.16\,\text{m}\\ z_3 &= 0.5 \times 2.4 = 1.2\,\text{m}\\ z_2 &= \frac{(2.16 - 1.2)}{1000} \times 900 + 1.2 = \underline{\underline{2.06\,\text{m}}}\ \text{say}\ \underline{\underline{2.0\,\text{m}}} \qquad (10.5)\end{aligned}$$

Proposed Design



ANSI Pipe Schedule
Inch units

OD = inches
Wall thickness = inches
Weight = lbs/ft
Vol/ft = ft^3

INCH UNITS

Phocéenne de métallurgie

9/11, 3e RUE - Z.I. - B.P. 61
13742 VITROLLES - FRANCE

Tél. : 42 79 40 00
Télex : 420255 F
Téléfax : 42 79 40 79

															Figures based on austenitic steel				
Nominal pipe size inches	OD inches	10	20	30	STD	40	60	XS	80	100	120	140	160	XXS	5S	10S	40S	80S	Vol/ft
1/8	0.406				0.068 0.24	0.068 0.24		0.095 0.31	0.095 0.31							0.049 0.19	0.068 0.24	0.095 0.32	0.0001
1/4	0.540				0.088 0.42	0.088 0.42		0.119 0.54	0.119 0.54							0.065 0.34	0.088 0.43	0.119 0.55	0.0002
3/8	0.675				0.091 0.57	0.091 0.57		0.126 0.74	0.126 0.74							0.065 0.43	0.091 0.58	0.126 0.75	0.0005
1/2	0.840				0.109 0.85	0.109 0.85		0.147 1.09	0.147 1.09				0.188 1.31	0.294 1.71	0.065 0.55	0.083 0.68	0.109 0.87	0.147 1.11	[illegible]
3/4	1.050				0.113 1.13	0.113 1.13		0.154 1.47	0.154 1.47				0.219 1.94	0.308 2.44	0.065 0.70	0.083 0.88	0.113 1.15	0.154 1.50	0.007
1	1.315				0.133 1.68	0.133 1.68		0.179 2.17	0.179 2.17				0.250 2.84	0.358 3.66	0.065 0.89	0.109 1.43	0.133 1.71	0.179 2.21	0.007
1 1/4	1.660				0.140 2.27	0.140 2.27		0.191 3.00	0.191 3.00				0.250 3.76	0.382 5.21	0.065 1.13	0.109 1.85	0.140 2.32	0.191 3.06	0.010
1 1/2	1.900				0.145 2.72	0.145 2.72		0.200 3.63	0.200 3.63				0.281 4.86	0.400 6.41	0.065 1.31	0.109 2.13	0.145 2.77	0.200 3.70	0.025
2	2.375				0.154 3.65	0.154 3.65		0.218 5.02	0.218 5.02				0.344 7.46	0.436 9.03	0.065 1.64	0.109 2.69	0.154 3.72	0.218 5.12	0.030
2 1/2	2.875				0.203 5.79	0.203 5.79		0.276 7.66	0.276 7.66				0.375 10.01	0.552 13.69	0.083 2.53	0.120 3.60	0.203 5.91	0.276 7.81	0.047
3	3.500				0.216 7.58	0.216 7.58		0.300 10.25	0.300 10.25				0.438 14.32	0.600 18.58	0.083 3.09	0.120 4.42	0.216 7.73	0.300 10.46	0.085
3 1/2	4.000				0.226 9.11	0.226 9.11		0.318 12.50	0.318 12.50				— —	— —	0.083 3.55	0.120 5.07	0.226 9.29	0.318 12.76	0.111
4	4.500				0.237 10.79	0.237 10.79		0.337 14.98	0.337 14.98		0.438 19.00		0.531 22.51	0.674 27.54	0.083 4.00	0.120 5.72	0.237 11.01	0.337 15.28	0.140
5	5.563				0.258 14.62	0.258 14.62		0.375 20.78	0.375 20.78		0.500 27.04		0.625 32.96	0.750 38.55	0.109 6.49	0.134 7.93	0.258 14.91	0.375 21.20	0.214
6	6.625				0.280 18.97	0.280 18.97		0.432 23.57	0.432 28.57		0.562 36.39		0.719 45.35	0.864 53.16	0.109 7.75	0.134 9.48	0.278 18.35	0.432 29.14	0.301
8	8.625		0.250 22.36	0.277 24.70	0.322 28.55	0.322 28.55	0.406 35.64	0.500 43.39	0.500 43.39	0.594 50.95	0.719 60.71	0.812 67.76	0.906 74.69	0.875 72.42	0.109 10.13	0.148 13.67	0.322 29.12	0.500 44.26	0.517
10	10.750		0.250 28.04	0.307 34.24	0.365 40.48	0.365 40.48	0.500 54.74	0.500 54.74	0.594 64.43	0.719 77.03	0.844 89.29	1.000 104.13	1.125 115.64	1.000 104.13	0.134 15.49	0.165 19.02	0.365 41.29	0.500 55.83	0.797
12	12.750		0.250 33.38	0.330 43.77	0.375 49.56	0.406 53.52	0.562 73.15	0.500 65.42	0.688 88.63	0.844 107.32	1.000 125.49	1.125 139.67	1.312 160.27	1.000 125.49	0.156 21.40	0.180 24.65	0.375 50.55	0.500 66.75	[illegible]
14	14.000	0.250 36.71	0.312 45.61	0.375 54.57	0.375 54.57	0.438 63.44	0.594 85.05	0.500 72.09	0.750 106.13	0.938 130.85	1.094 150.79	1.250 170.21	1.406 189.11		0.156 23.53	0.188 28.28			1.266
16	16.000	0.250 42.05	0.312 52.27	0.375 62.58	0.375 62.58	0.500 82.77	0.656 107.50	0.500 82.77	0.844 136.61	1.031 164.82	1.219 192.43	1.438 223.64	1.594 245.25		0.165 28.46	0.188 32.39			1.726
18	18.000	0.250 47.39	0.312 58.94	0.438 82.15	0.375 70.59	0.562 104.67	0.750 138.17	0.500 93.45	0.938 170.92	1.156 207.96	1.375 244.14	1.562 274.22	1.781 308.50		0.165 32.06	0.188 36.48			2.239
20	20.000	0.250 52.73	0.375 78.60	0.500 104.13	0.375 78.60	0.594 123.11	0.812 166.40	0.500 104.13	1.031 208.87	1.281 256.10	1.500 296.37	1.750 341.09	1.969 379.17		0.188 40.58	0.218 46.98			2.772
22	22.000	0.250 58.07	0.375 86.61	0.500 114.81	0.375 86.61	— —	0.875 197.41	0.500 114.81	1.125 250.81	1.375 302.68	1.625 353.61	1.875 403.00	2.125 451.06		0.188 44.68	0.218 51.72			3.369
24	24.000	0.250 63.41	0.375 94.62	0.562 140.68	0.375 94.62	0.688 171.29	0.969 238.35	0.500 125.49	1.219 296.58	1.531 367.39	1.812 429.39	2.062 483.12	2.344 542.13		0.218 56.48	0.250 64.68			4.005
26	26.000	0.312 85.60	0.500 136.17	— —	0.375 102.63	— —		0.500 136.17											4.683
28	28.000	0.312 92.26	0.500 146.85	0.625 182.73	0.375 110.64	— —		0.500 146.85											5.437
30	30.000	0.312 98.93	0.500 157.53	0.625 196.08	0.375 118.65	— —		0.500 157.53							0.250 81.02	0.312 100.91			6.244
32	32.000	0.312 105.59	0.500 168.21	0.625 209.43	0.375 126.66	0.688 230.08		0.500 168.21											7.105
34	34.000	0.312 112.25	0.500 178.89	0.625 222.78	0.375 134.67	0.688 244.77		0.500 178.89											8.031
36	36.000	0.312 118.92	0.500 189.57	0.625 236.13	0.375 142.68	0.750 282.35		0.500 189.57											8.980
38	38.000				0.375 150.69			0.500 200.25											10.023
40	40.000				0.375 158.70			0.500 210.93											[illegible]
42	42.000				0.375 166.71			0.500 221.61											12.267
44	44.000				0.375 174.72			0.500 232.29											13.447
46	46.000				0.375 182.73			0.500 242.87											14.686
48	48.000				0.375 190.74			0.500 253.65											15.989