PRESSURE VESSEL

Pressure Vessel Design

- A pressure vessel is any vessel that falls under the definition laid down in the ASME Boiler and Pressure Vessel Code, Section VIII, Rules for the Construction of Pressure Vessels (ASME BPV Code Sec. VIII)
- The definition applies to most process reactors, distillation columns, separators (flashes and decanters), pressurized storage vessels and heat exchangers

Source: UOP

Isn’t This Something to Leave to the Mechanical Engineers?

- Chemical engineers are usually not properly trained or qualified to carry out detailed mechanical design of vessels. Most mechanical designs are completed by specialists in later phases of design

But

- The process design engineer needs to understand pressure vessel design in order to generate good cost estimates (e.g. in Aspen ICARUS)
- Costs can vary discontinuously with vessel design
    - A 10°C change in temperature could double the vessel cost if it causes a change in code!
    - Adding a component could cause a change in metallurgy that would mean moving to a more expensive code design
- The process engineer will end up specifying the main constraints on the vessel design: if you don’t know how to do this properly, you can’t really design anything

PRESSURE VESSELS

- Pressure vessels are the containers for fluids under high pressure.

- They are used in a variety of industries like

  - Petroleum refining
  - Chemical
  - Power
  - Food & beverage
  - Pharmaceutical

Pressure Vessel Design

- Pressure Vessel Design Codes
- Vessel Geometry & Construction
- Strength of Materials
- Vessel Specifications
- Materials of Construction
- Pressure Vessel Design Rules
- Fabrication, Inspection and Testing

ASME Boiler and Pressure Vessel Code

- ASME BPV Code is the legally required standard for pressure vessel design, fabrication, inspection and testing in North America

Section	
I	Rules for construction of power boilers
II	Materials
III	Nuclear power plant components
IV	Rules for construction of heating boilers
V	Nondestructive examination
VI	Recommended rules for the care and operation of heating boilers
VII	Recommended guidelines for the care of power boilers
VIII	Rules for the construction of pressure vessels
	Division 1
	Division 2 — Alternative rules
	Division 3 — Alternative rules for the construction of high pressure vessels
IX	Welding and brazing qualifications
X	Fiber-reinforced plastic vessels
XI	Rules for in service inspection of nuclear power plant components
XII	Rules for construction and continued service of transport tanks

Allowable stresses are given in Sec. II

Often used for bio-reactors

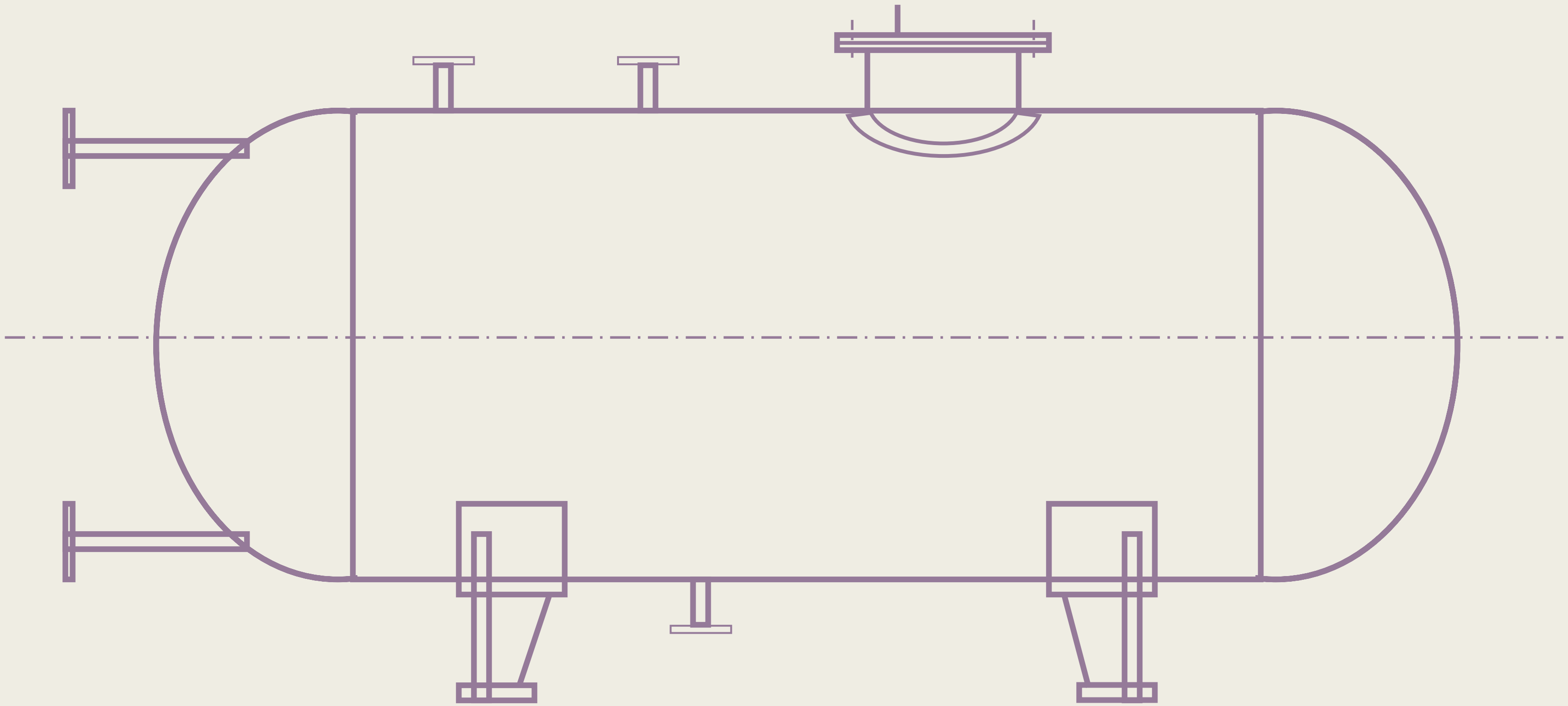
TYPES OF PRESSURE VESSELS

There are three main types of pressure vessels in general

- Horizontal Pressure Vessels
- Vertical Pressure Vessels
- Spherical Pressure vessels

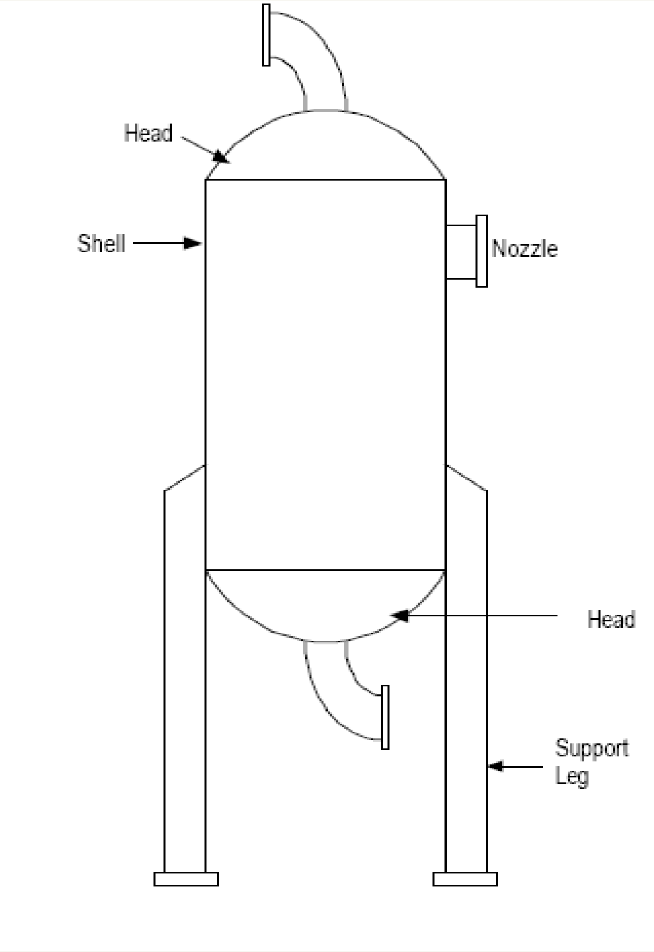
However there are some special types of Vessels like Regeneration Tower, Reactors but these names are given according to their use only.

HORIZONTAL PRESSURE VESSEL



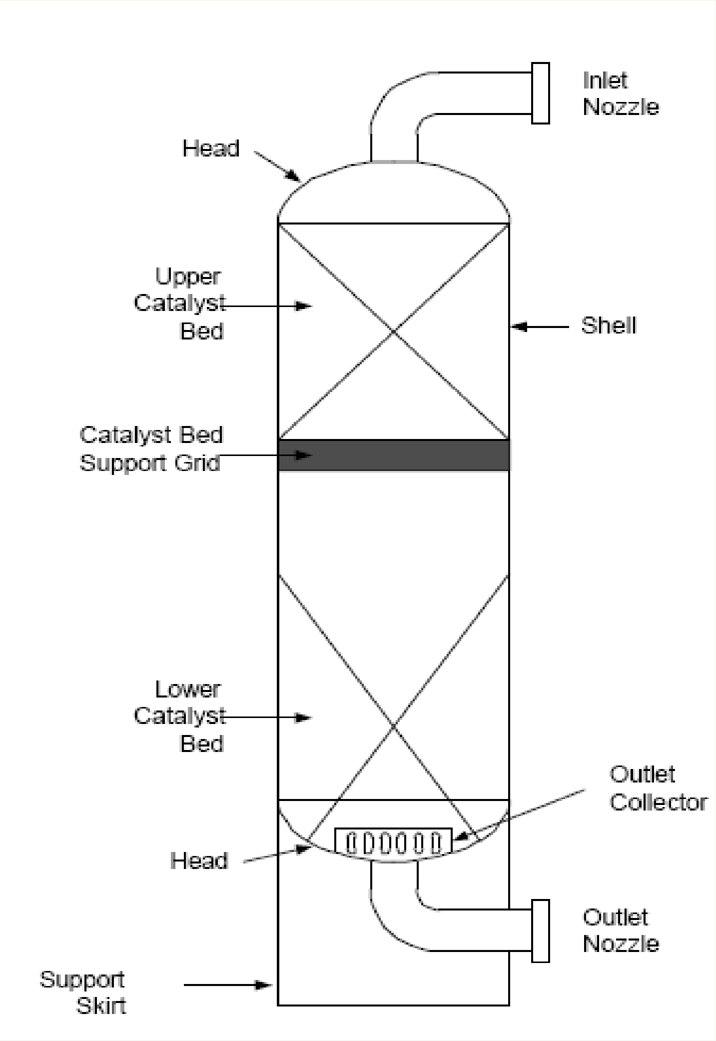
VERTICAL PRESSURE VESSEL

- The max. Shell length to diameter ratio for a small vertical drum is about 5 : 1



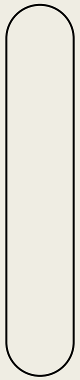
VERTICAL REACTOR

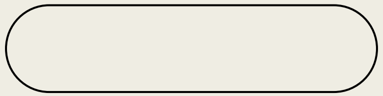
- Figure shows a typical reactor vessel with a cylindrical shell.
- The process fluid undergoes a chemical reaction inside a reactor.
- This reaction is normally facilitated by the presence of a catalyst which is held in one or more catalyst beds.



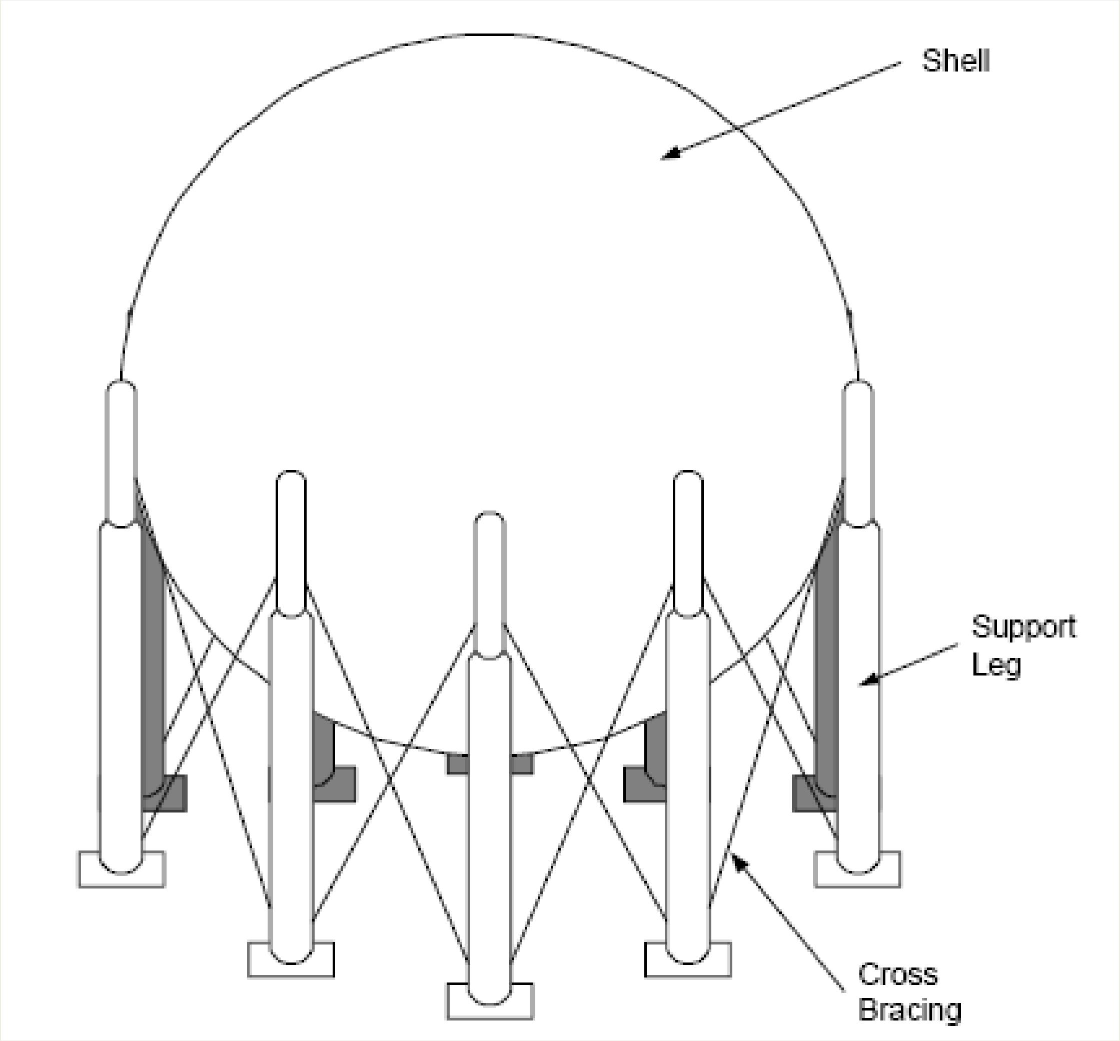
Vessel Orientation

- Usually vertical
  - *Easier to distribute fluids across a smaller cross section*
  - *Smaller plot space*
- Reasons for using horizontal vessels
  - *To promote phase separation*
    - Increased cross section = lower vertical velocity = less entrainment
    - Decanters, settling tanks, separators, flash vessels
  - *To allow internals to be pulled for cleaning*
    - Heat exchangers





SPHERICAL PRESSURIZED STORAGE VESSEL

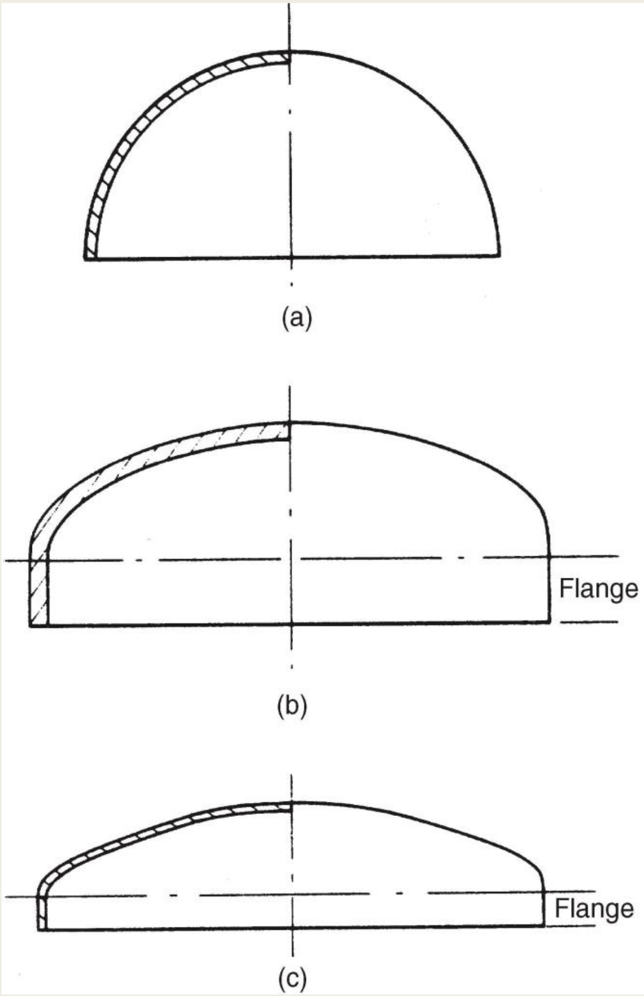


MAIN COMPONENTS OF PRESSURE VESSEL

Following are the main components of pressure Vessels in general

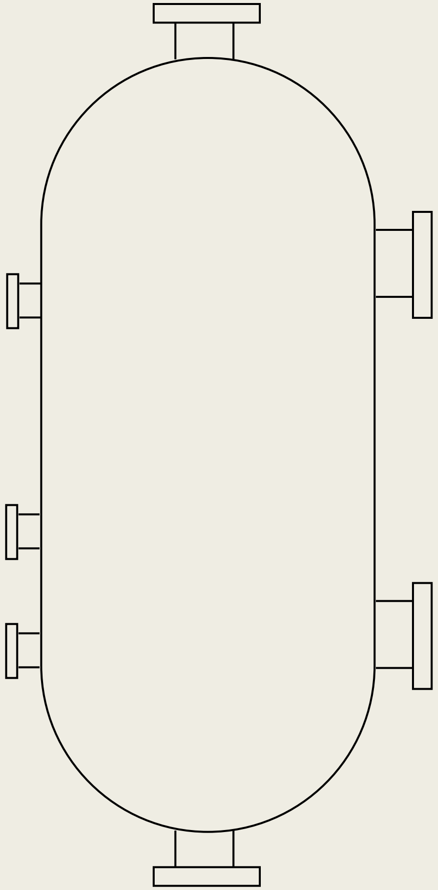
- Shell
- Head
- Nozzle
- Support

Head (Closure) Designs



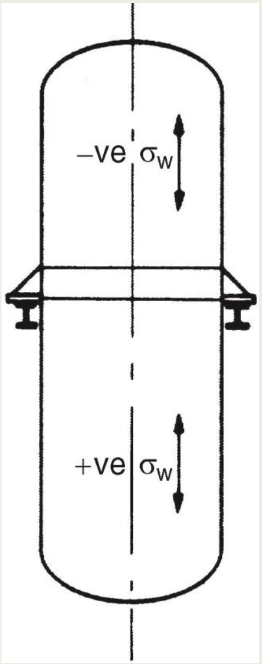
- Hemispherical
  - *Good for high pressures*
  - *Higher internal volume*
  - *Most expensive to form & join to shell*
  - *Half the thickness of the shell*
- Ellipsoidal
  - *Cheaper than hemispherical and less internal volume*
  - *Depth is half diameter*
  - *Same thickness as shell*
  - *Most common type > 15 bar*
- Torispherical
  - *Part torus, part sphere*
  - *Similar to elliptical, but cheaper to fabricate*
  - *Cheapest for pressures less than 15 bar*

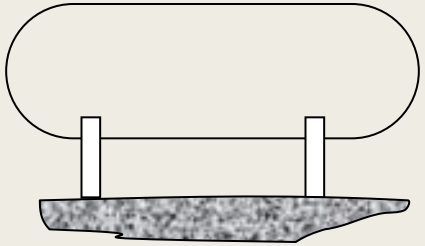
Nozzles

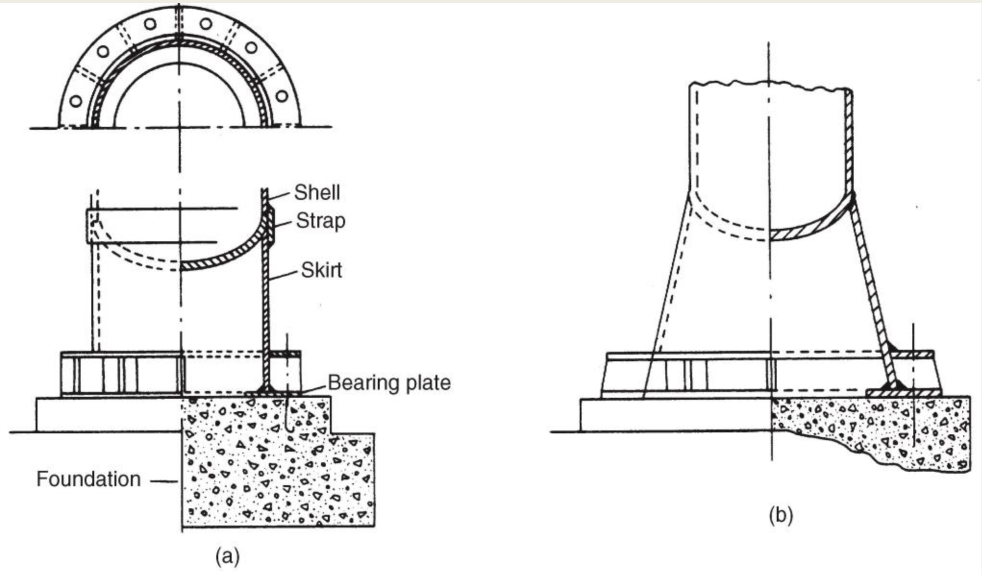


- Vessel needs nozzles for
  - *Feeds, Products*
  - *Hot &/or cold utilities*
  - *Manways, bursting disks, relief valves*
  - *Instruments*
    - Pressure, Level, Thermowells
    - Sample points
- More nozzles = more cost
- Nozzles are usually on side of vessel, away from weld lines, usually perpendicular to shell
- Nozzles may or may not be flanged (as shown) depending on joint type
- The number & location of nozzles are usually specified by the process engineer

Vessel Supports

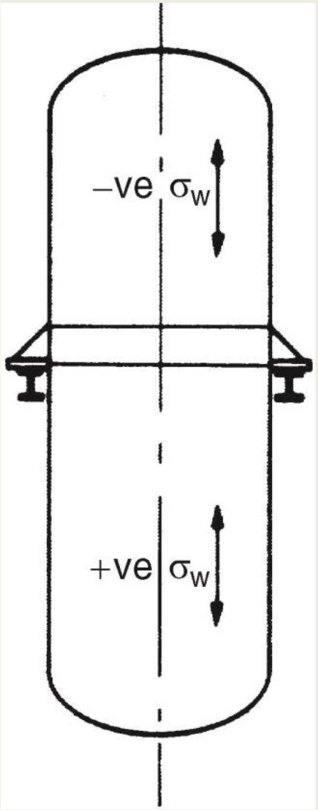






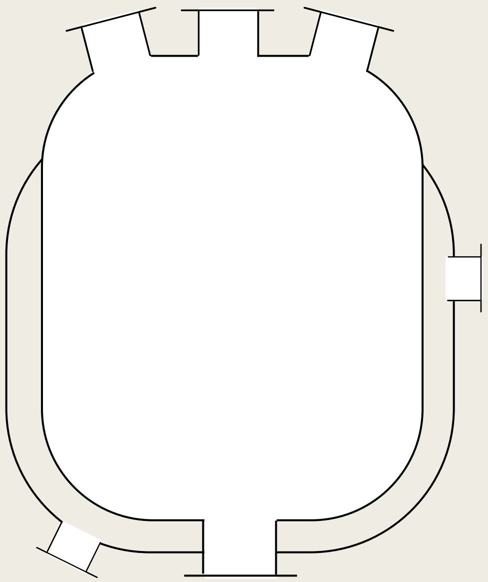
- Supports must allow for thermal expansion in operation
- Smaller vessels are usually supported on beams – a support ring or brackets are welded to the vessel
- Horizontal vessels often rest on saddles
- Tall vertical vessels are often supported using a skirt rather than legs. Can you think why?

Vessel Supports



- Note that if the vessel rests on a beam then the part of the vessel below the support ring is hanging and the wall is in tension from the weight of material in the vessel, the dead weight of the vessel itself and the internal pressure
- The part of the vessel above the support ring is supported and the wall is in compression from the dead weight (but probably in tension from internal pressure)

Jacketed Vessels



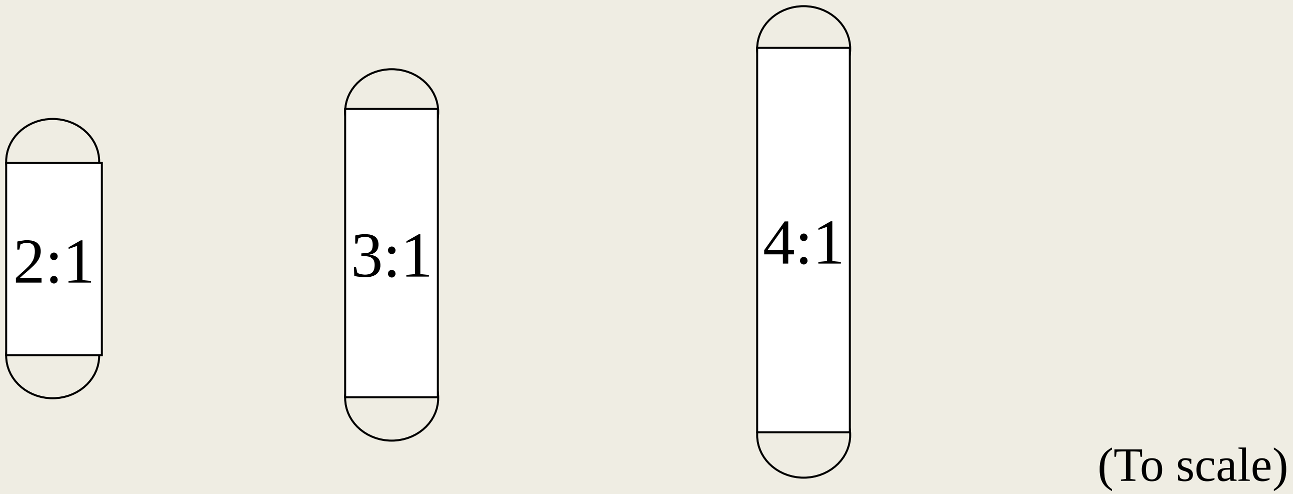
- Heating or cooling jackets are often used for smaller vessels such as stirred tank reactors
- If the jacket can have higher pressure than the vessel then the vessel walls must be designed for compressive stresses
  - *Internal stiffening rings are often used for vessels subject to external pressure*
  - *For small vessels the walls are just made thicker*

Vessel Internals

- Most vessels have at least some internals
  - Distillation trays
  - Packing supports
  - Distribution grids
  - Heating or cooling coils
- These may require support rings welded to the inside of the vessel
- The internals & support rings need to be considered when calculating vessel weights for stress analysis

Pressure Vessel Shape

- Most pressure vessels are at least 2:1 cylinders: 3:1 or 4:1 are most common:



- Distillation columns are obviously an exception: diameter is set by flooding correlations and height by number of trays

Loads Causing Stresses on Pressure Vessel Walls

- Internal or external pressure
- Dead weight of vessel
- Weight of contents under normal or upset conditions
- Weight of contents during hydraulic testing
- Weight of internals
- Weight of attached equipment (piping, decks, ladders, etc)
- Stresses at geometric discontinuities
- Bending moments due to supports
- Thermal expansion, differential thermal expansion
- Cyclic loads due to pressure or temperature changes
- Wind & snow loads
- Seismic loads
- Residual stresses from manufacture
- Loads due to friction (solids flow)

All these must be combined to determine principal stresses

Vessel Specifications Set By the Process Engineer

- The process engineer will usually specify the following parameters based on process requirements:
  - *Vessel size and shape (volume, L and D)*
  - *Vessel orientation and elevation*
  - *Maximum and minimum design pressure*
  - *Maximum and minimum design temperature*
  - *Number of nozzles needed (& location)*
  - *Vessel internals*

  And often also:
  - *Material of construction*
  - *Corrosion allowance*
- There is often a lot of dialogue with the mechanical engineer to set the final specifications

Materials Selection Criteria

- Safety
  - *Material must have sufficient strength at design conditions*
  - *Material must be able to withstand variation (or cycling) in process conditions*
  - *Material must have sufficient corrosion resistance to survive in service between inspection intervals*
- Ease of fabrication
- Availability in standard sizes (plates, sections, tubes)
- Cost
  - *Includes initial cost and cost of periodic replacement*

Commonly Used Materials

- Steels
  - *Carbon steel, Killed carbon steel – cheap, widely available*
  - *Low chrome alloys (<9% Cr) – better corrosion resistance than CS, KCS*
  - *Stainless steels:*
    - 304 – cheapest austenitic stainless steel
    - 316 – better corrosion resistance than 304, more expensive
    - 410
- Nickel Alloys
  - *Inconel, Incolloy – high temperature oxidizing environments*
  - *Monel, Hastelloy – expensive, but high corrosion resistance, used for strong acids*
- Other metals such as aluminum and titanium are used for special applications. Fiber reinforced plastics are used for some low temperature & pressure applications

Determining Wall Thickness

- Under ASME BPV Code Sec. VIII D.1, minimum wall thickness is 1/16” (1.5mm) with no corrosion allowance
- Most pressure vessels require much thicker walls to withstand governing load
  - *High pressure vessels: internal pressure usually governs*
  - *Thickness required to resist vacuum usually governs for lower pressure vessels*
  - *For vessels designed for low pressure, no vacuum, then analysis of principal stresses may be needed*
  - *Usual procedure is to design for internal pressure (or vacuum), round up to nearest available standard size and then check for other loads*

Design for Internal Pressure

- ASME BPV Code Sec. VIII D.1 specifies using the larger of the shell thicknesses calculated
  - *For hoop stress*

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

  - *or for longitudinal stress*

$$t = \frac{P_i\, D_i}{4SE + 0.8 P_i}$$

S is the maximum allowable stress
E is the welded joint efficiency

- Values of S are tabulated in ASME BPV Code Sec.II for different materials as function of temperature

Closures Subject to Internal Pressure

- Hemispherical heads

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

- Ellipsoidal heads

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

- Torispherical heads

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

R_c is the crown radius:

Software for Pressure Vessel Design

- Rules for external pressure, combined loads are more complex
- Design methods and maximum allowable stresses are coded into software used by specialist designers, such as:
  - COMPRESS (Codeware Inc.) has free demo version http://www.codeware.com/support/tutorials/compress_video_tutorial.html
  - Pressure Vessel Suite (Computer Engineering Inc.)
  - PVElite and CodeCalc (COADE Inc.)
- Simple ASME BPV Code Sec. VIII D.1 methods are available in Aspen ICARUS
  - Good enough for an initial cost estimate if the process engineer puts in realistic vessel specifications
  - Useful for checking to see if changes to specifications give cost discontinuities
  - Not good enough for detailed vessel design

Vessel Manufacture

- Shell is usually made by rolling plate and then welding along a seam:

  - *Difficult to form small diameters or thick shells by this method*
  - *Long vessels are usually made in 8’ sections and butt welded*
- Thicker vessels are made by more expensive drum forging – direct from ingots
- Closures are usually forged
  - *Hence restricted to increments of 6” in diameter*
- Nozzles, support rings etc. are welded on to shell and heads

Post Weld Heat Treating (PWHT)

- Forming and joining (welding) can leave residual stresses in the metal
- Post-weld heat treatment is used to relax these stresses
- Guidelines for PWHT are given in the ASME BPV Code Sec. VIII D.1 Part UW-40
- PWHT requirements depend on material and thickness at weld:
  - *Over 38mm for carbon steel*
  - *Over 16mm for low alloy*

Classification of vessels

1. According to pressure and its type

   - Internal Pressure Vessel

   - External Pressure Vessel

Internal Pressure Vessel

—— vessels where the media pressure

inside the vessel is larger than that outside

(gauge pressure).

Low pressure vessel (L):

$0.1 \leq P < 1.6$ MPa

Medium pressure vessel (M):

$1.6 \leq P < 10$ MPa

High pressure vessel (H):

$10 \leq P < 100$ MPa

Ultra-high pressure vessel (U):

$P \geq 100$ MPa

External Pressure Vessel

—— vessels where the media pressure inside the vessel is lower than that outside (gauge pressure). When the internal pressure < 0.1 MPa (absolute pressure), such vessels are called Vacuum Vessel.

2. According to temperature

- Maximum:
  - Highest mean metal temperature expected in operation, including transient conditions, plus a margin
  - Margin is typically plus 50°F
- Minimum
  - Lowest mean metal temperature expected in operation, including transient conditions, upsets, auto-refrigeration, climatic conditions, anything else that could cause cooling, minus a margin
  - Margin is typically -25°F
  - MDMT: minimum design metal temperature is important as metals can become brittle at low temperatures
- Designer should allow for possible failure of upstream equipment (e.g., loss of coolant on upstream cooler)